Variation of Fundamental Constants

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Motivation

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

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

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

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

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

Atomic transition frequencies

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:

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

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!

Request for laboratory measurements: shopping list arxiv: physics/0408017

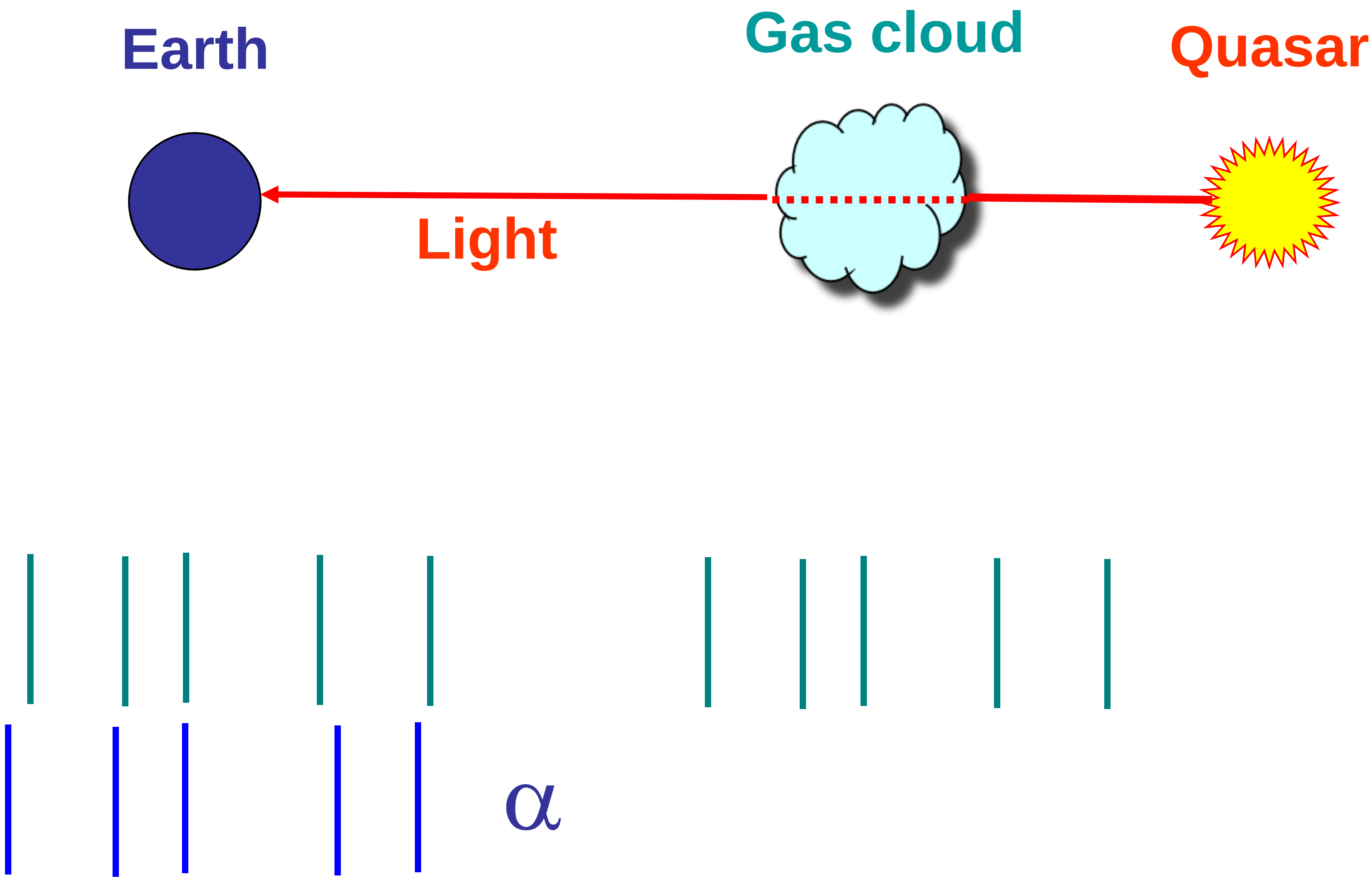
- More accurate measurements of **UV transition frequencies**
- Measurements of **isotope shifts**

  Cosmological evolution of isotope abundances in the Universe:

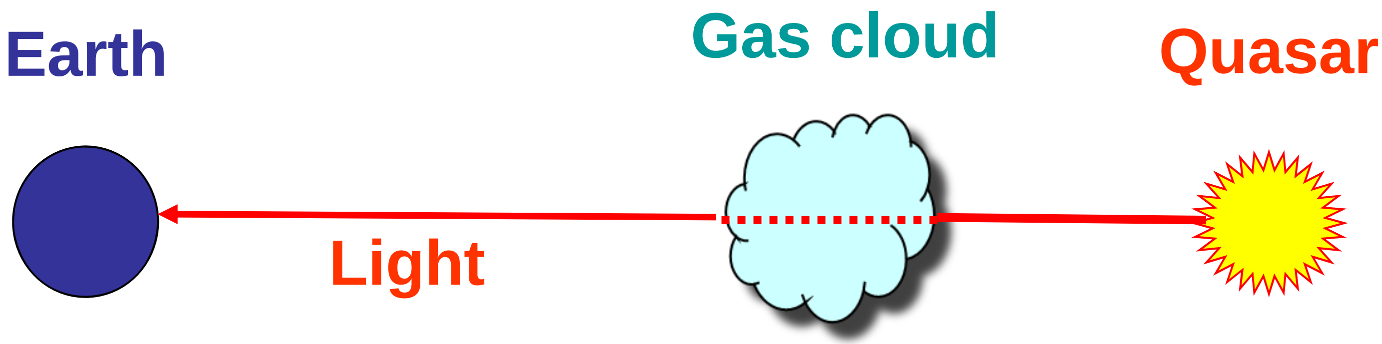
  a). Systematics for the variation of α

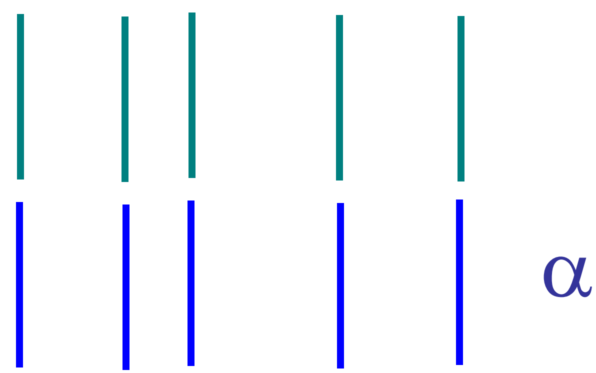
  b). Test of theories of nuclear reactions in stars and supernovae
- **Oscillator strengths** to fit column densities

Quasar absorption spectra

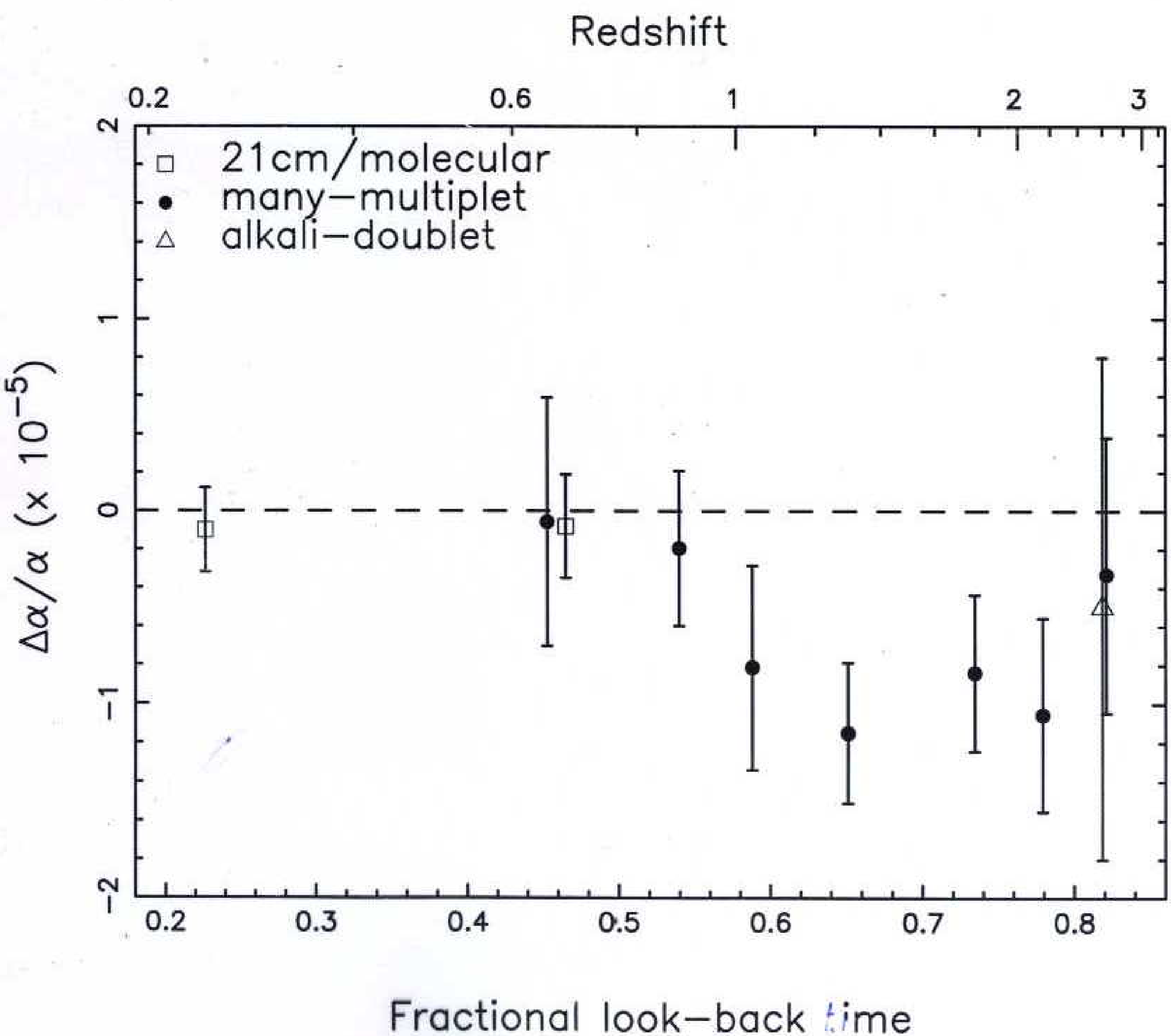


Quasar absorption spectra





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


Redshift
0.2
0.6
1
2
3
21cm/molecular
many-multiplet
alkali-doublet
Δα/α (x 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

New interpretation: Spatial variation

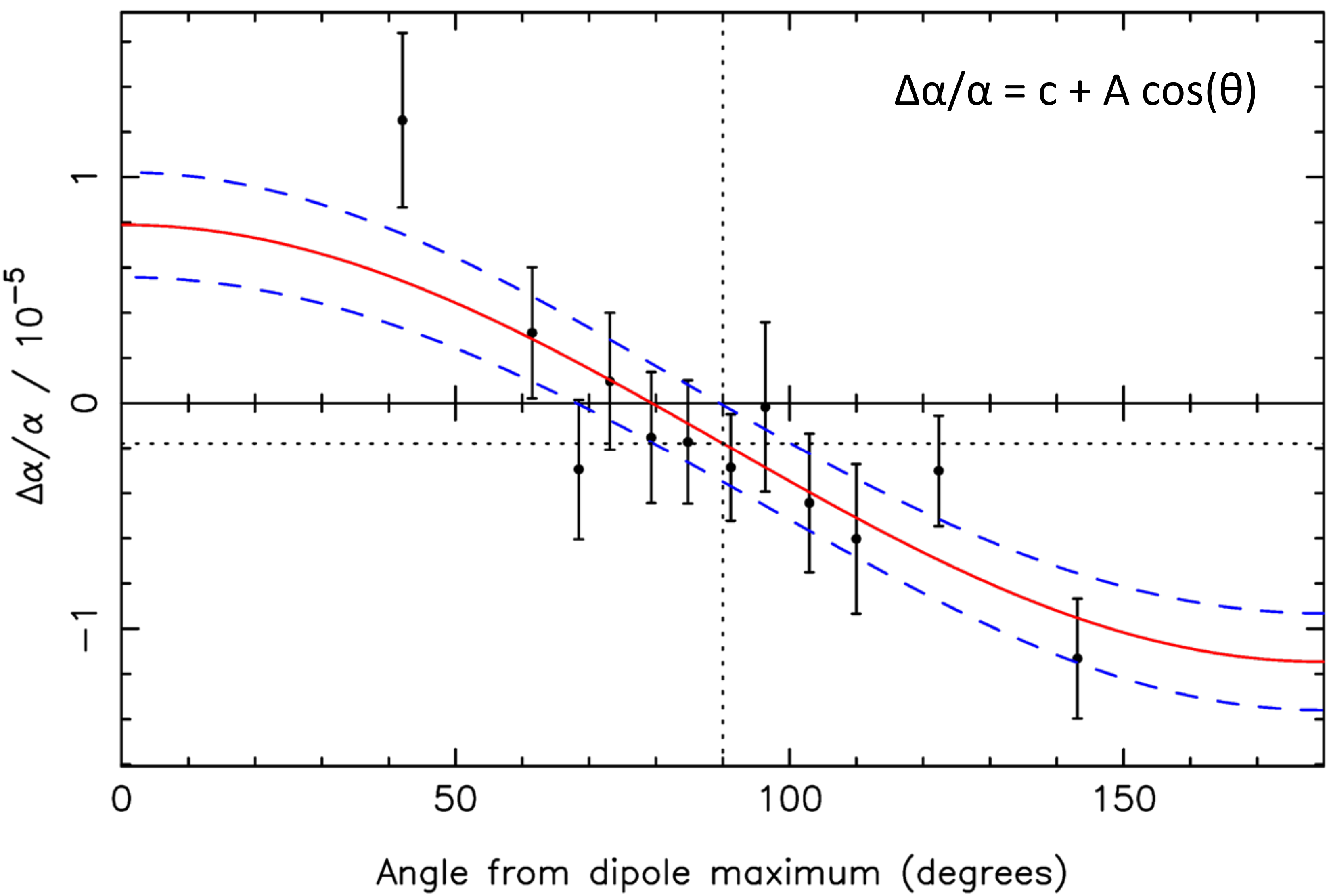
Northern+(new)Southern hemisphere data:
Linear variation with distance along some direction $z = r \cos(\phi)$, $r = ct$ (Gly),

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

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

Results for m_q / Λ_{QCD} and m_e / Λ_{QCD}
Big Bang Nucleosynthsis data and H_2 molecule data are consitent with the direction of the dipole.

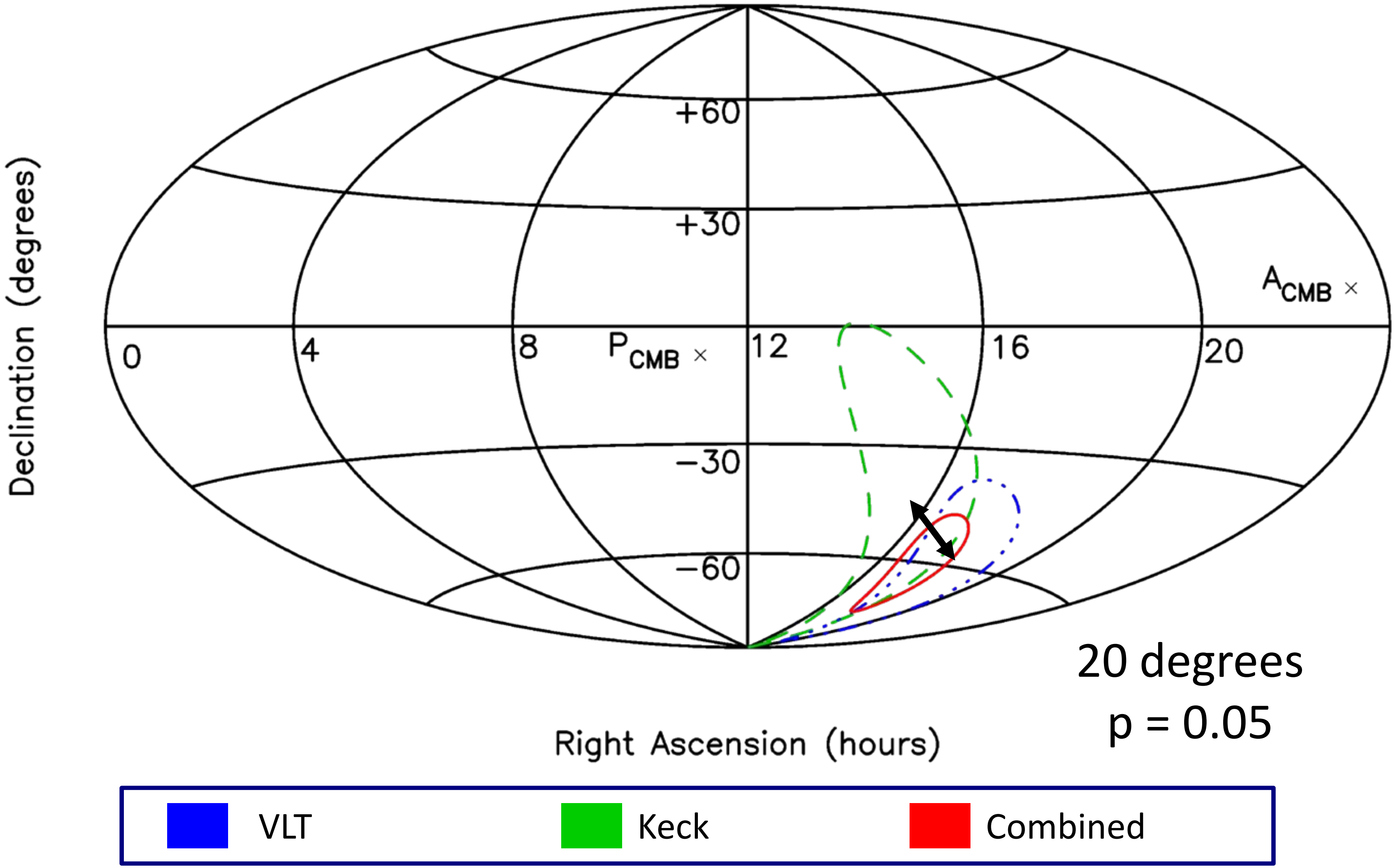
4.1σ evidence for a Δα/α dipole from VLT + Keck



Julian King, UNSW

☺

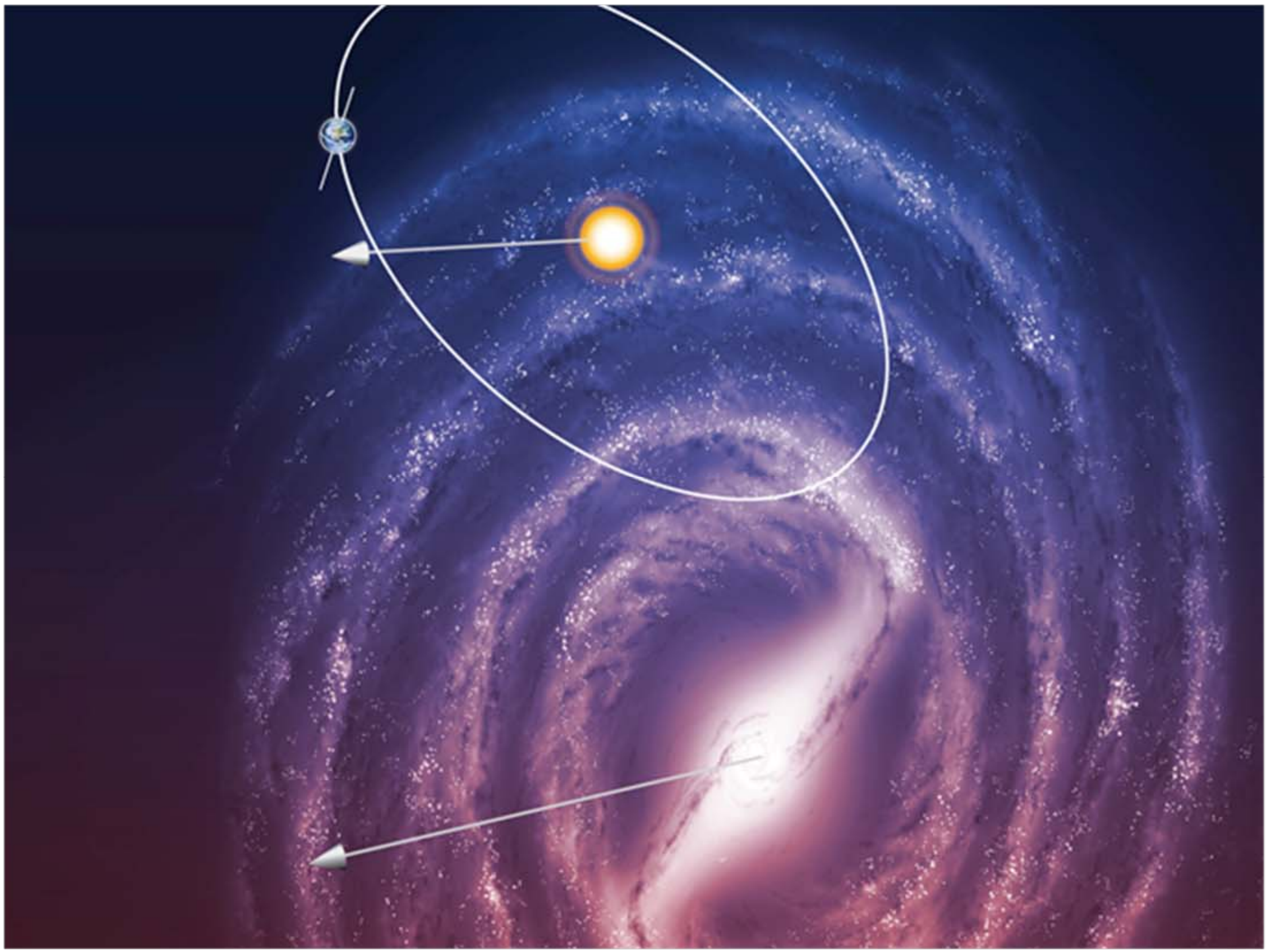
The Keck & VLT dipoles point in the same direction



20 degrees
$p = 0.05$

☺

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
ΔE_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(ϕ)=0.23
Dipole in space: ΔE_r =(10 R - 1) meV

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

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 and nuclear radii

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

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

Results for variation of fundamental constants

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

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

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

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

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

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

Porsev, Flambaum, Torgerson

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 sensitivity enhancement up to 500

Berengut, Dzuba, Flambaum, Porsev

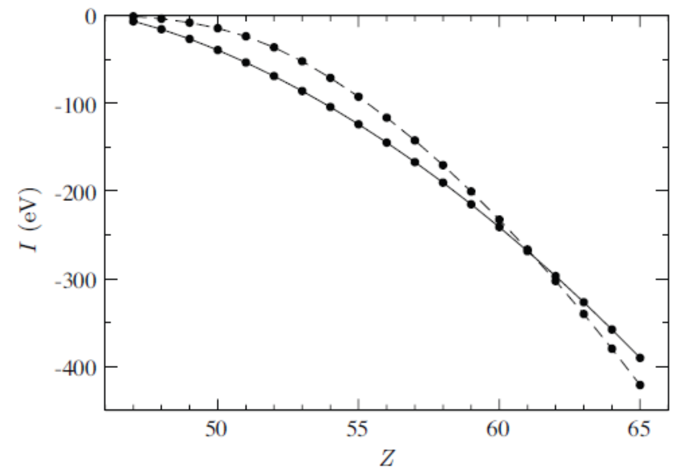


FIG. 2. Dirac-Fock ionisation energies of 5s (solid) and 4$f_{7/2}$ (dashed) levels for the Ag isoelectronic sequence.

arXiv:1007.1068

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,Felmeier,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

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}

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

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

Close narrow levels in molecules

Conclusions

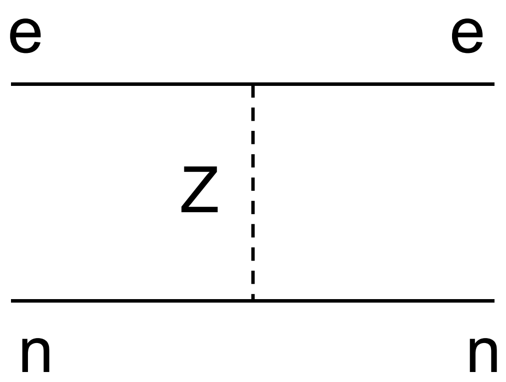
- Spatial dipole in quasar data provides alpha variation for atomic clocks due to Earth motion at the level 10^{-18} per year.

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,…

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!

Calculation [Dzuba,Flambaum,Ginges, 2002]

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

Cs Boulder

$\Rightarrow Q_W - Q_W^{SM} = 1.1\ \sigma$

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;

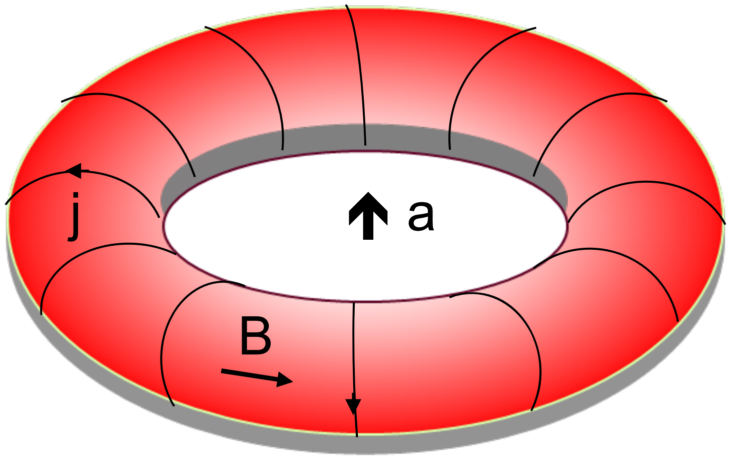
Ra,Ra^+,Fr Argonne, Groningen,TRIUMF?

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!

Enhancement of nuclear anapole effects in molecules

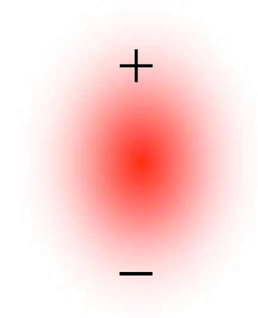
10^5 enhancement of the nuclear anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity.

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.

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 $d(Tl) = -500\, d_e$

Experiment – Berkeley. Our accurate many-body calculations for Tl,Fr,Cs,…

- Molecules –close rotational levels,

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

$\Omega = 1/2$	10^7	YbF	London
$\Omega = 1$	10^{10}	PbO,ThO	Yale,Harvard
$\Omega = 2$	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

- Schiff theorem $V=d_N E_N=0$
- Extension for ions:

Ion acceleration $a= Z_i eE/M$

Nucleus acceleration $a=Z eE_N/M$

$V=d_N E_N=d_N E Z_i/Z$

EDMs of atoms of experimental interest

Z	Atom	[S/(e fm3)]e cm	[10^{-25} η] 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 cm η,

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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