

Cosmic time dependence of fundamental constants

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Keck telescope (Australia, England, US)

"many multiplet method" (Webb, Wolfe)

fine-structure of Fe, Ni, Mg, Sn, A

~150 quasars (\rightarrow 11 billion years in time)

$$(-0.54 \pm 0.12)$$

$$\frac{\Delta \alpha}{\alpha} = (-0.72 \pm 0.18) \cdot 10^{-5}$$

$$\alpha = 1/137,036\text{---}99976 \quad (\text{today})$$

$$\text{early } \alpha \approx 1/137,037 \quad (\text{not. } 036)$$

$$\text{Linear app.: } \frac{\dot{\alpha}}{\alpha} \approx 1.2 \cdot 10^{-15} \text{ per year}$$

Example

Fine Structure Constant

→ Sommerfeld 1916

$$\alpha = \frac{e^2}{\hbar c}$$

Originally it was assumed:

$$1/\alpha = 137$$

(integer!)

Philosophy and numerology:

Eddington: $137 > 136 = \text{Nr of}$

$$\text{charged objects} \quad \alpha^{-1} = \frac{16^2 - 16}{2} + 16 = 136$$

Pauli (1958): Nr 137.....

(A)

Lederer: 137 Euler Road, JL

Feynman: 137 (How little we know)

Time Dependence of constants:

long history

30's: Dirac, Milne ($\rightarrow G$)

P. Jordan (other constants)

L. Landau (α : in conn. to renorm.)

$$\alpha = \frac{e^2}{\hbar c} \quad \hbar, c \rightarrow 1 \text{ in suitable systems}$$

\rightarrow unlikely, that \hbar or c depend on time (?)

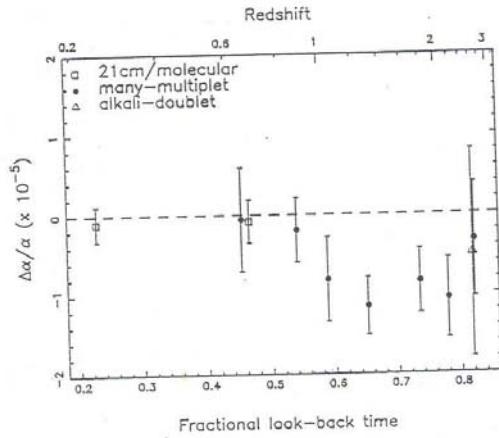
\rightarrow time-dependence of e

Grand unification:

$$SU(3) \times SU(2) \times U(1) \subset \begin{matrix} SU(5) \\ SO(10) \end{matrix}$$

Sample	Method	N_{abs}	Redshift	$\Delta\alpha/\alpha$
FeII/MgII	MM	28	$0.5 < z < 1.8$	-0.70 ± 0.23
NiII/CrII/ZnII	MM	21	$1.8 < z < 3.5$	-0.76 ± 0.28
SiIV	AD	21	$2.0 < z < 3.0$	-0.5 ± 1.3
21cm/mm	radio	2	$0.25, 0.68$	-0.10 ± 0.17

TABLE I: Summary of results for 4 independent samples. Values of $\Delta\alpha/\alpha$ are weighted means in units of 10^{-5} . MM and AD indicate "many-multiplet" and "alkali-doublet". N_{abs} is the number of absorption systems in each sample.



13.9 Gyr

FIG. 1: $\Delta\alpha/\alpha$ vs. fractional look-back time to the Big Bang. The conversion between redshift and look-back time assumes $H_0 = 68 \text{ km/s/Mpc}$, $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$, so that the age of the universe is 13.9 Gyr. 72 quasar absorption systems contribute to this binned-data plot. The hollow squares correspond to two HI 21cm and molecular absorption systems [16]. Those points assume no change in g_B , so should be interpreted with caution. The 7 solid circles are binned results for 49 quasar absorption systems. The lower redshift points (below $z \approx 1.6$) are based on (MgII/FeII) and the higher redshift points on (ZnII, CrII, NiII, AlIII, AlII, SiIV) [13]. 28 of these 49 systems correspond to the sample used in [4]. The hollow triangle represents the average over 21 quasar SiIV absorption doublets using the alkali doublet method [14].

Oklo

Natural reactor in Gabon (Africa)

Investigated since ~ 1970 by

French physicists. (Active: $\sim 2.6 \times 10^9$ years ago)

Samarium: decay depends
strongly on nuclear resonance

Resonance position cannot have
changed much

Dyson-Damour: $\frac{\alpha}{2} < 10^{-16}$ (10^{-12} ?)

(if no other pos. change)

→ Problem with astrophysics

Change of Λ : effects could
cancel, if signs of $\frac{\alpha}{2}, \frac{1}{\Lambda}$ different.

→ Oklo constraint questionable

Change of α :

C1

$M_n - M_p$ affected

$$M_n - M_p = (m_d - m_u) \text{ const.} - \alpha \cdot A \cdot \text{const.}$$

$(\downarrow \sim 2 \text{ MeV})$

$M_n - M_p \rightarrow (\rightarrow \text{nucleosynthesis})$

$$e^2 = \frac{g g'}{\sqrt{g^2 + g'^2}}, \quad U_1 \rightarrow SU(2) \times U(1)$$

$g \qquad g'$

Which $g^{(c)}$ is affected? (Both?)

G_F affected (\rightarrow nucleosynthesis)

$$SU(3)^c \times SU(2) \times U(1) \subset SO(10) \quad (?)$$

$\rightarrow \tilde{g}$ affected

$\rightarrow g_s$ affected (Λ_c)

$\rightarrow M_p \downarrow$

Systematic analysis needed!

1/Kopplungskonstante

$1/\text{coupling constant}$

$$1/\alpha_{\text{GUT}} \approx 40$$

$$1/\alpha$$

$$(3/8)(1/\alpha_{\text{em}})$$

$$1/\alpha_w$$

$$1/\alpha_s$$

Grosse Vereinigung

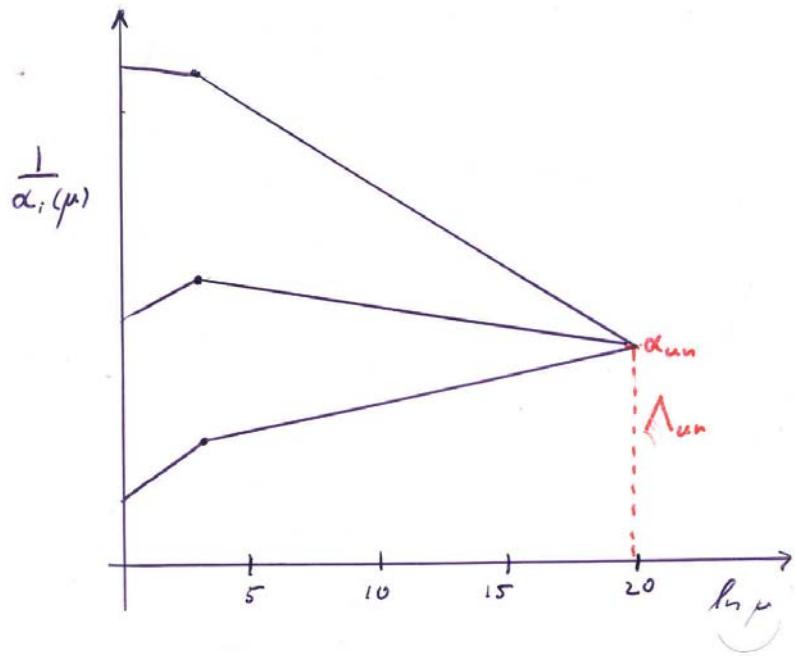
grand unif.

$$10^0 \quad 10^{-5} \quad 10^{-10} \quad 10^{-15} \quad \text{GeV}$$

Wechselwirkungsenergie

• Experimentelle Resultate exp. result

— Stellungen aus Renormierungstheorie
 $\text{dep. on ren. theory}$



Example $SU(5)$ with supersymmetry
at $\mu > 1$ TeV

(different, but possible pattern for $SO(10)$
without supersymmetry)

Cosmic Time Dependence of α :

a) time dependence of α_{un}

b) time dependence of Λ_{un}

Colmet, F.

Langacker, Seyer, Strauss

In general:

$$\frac{1}{\alpha} \frac{\dot{\alpha}}{\alpha} = \frac{8}{3} \frac{1}{\alpha_s} \frac{\dot{\alpha}_s}{\alpha_s} - \frac{1}{2\pi} \left(b_2^s + \frac{5}{3} b_1^s - \frac{8}{3} b_3^s \right) \frac{\dot{\Lambda}_{cut}}{\Lambda_{cut}}$$

$$\dot{\Lambda}_{cut} = 0$$

$$\frac{1}{\alpha} \frac{\dot{\alpha}}{\alpha} = \frac{8}{3} \frac{1}{\alpha_s} \frac{\dot{\alpha}_s}{\alpha_s}$$

$$\frac{\dot{\Lambda}}{\Lambda} \approx +38,8 \frac{\dot{\alpha}}{\alpha}$$

→ Magnetic Moments of Nuclei:

$$\frac{\mu_p}{\mu_p} = \frac{\mu_N}{\mu_N} \approx 38,8 \frac{\dot{\alpha}}{\alpha} \sim 3,9 \cdot 10^{-14} / \text{year}$$

α_{un} invariant, charge of Λ_{un} :

$$\frac{\dot{\Lambda}}{\Lambda} \approx -31 \cdot \frac{\dot{\alpha}}{\alpha}$$

(sign change!)

H2

- Finally, it should be mentioned that the scale of supersymmetry could also vary with time. One obtains:

$$\frac{1}{\alpha_i} \frac{\dot{\alpha}_i}{\alpha_i} = \left[\frac{1}{\alpha_u} \frac{\dot{\alpha}_u}{\alpha_u} - \frac{b_i^S}{2\pi} \frac{\dot{\Lambda}_G}{\Lambda_G} \right] + \frac{1}{2\pi} (b_i^S - b_i^{SM}) \frac{\dot{\Lambda}_S}{\Lambda_S} \theta(\Lambda_S - \mu).$$

However without a specific model for supersymmetry breaking relating the supersymmetry breaking scale to e.g. the GUT scale, this expression is not very useful.

- In particular if the physics generating a time variation of α was taking place between the GUT scale and the scale for supersymmetry breaking, our analysis might not be very reliable as there would then be no reason to assume that quantum field theory remains valid between these two scales.
- One case is of particular interest: the time variation of α is related to a time variation of the unification scale.
- the GUT scale could be related in specific models to vacuum expectation values of scalar fields. Since the universe expands, one might expect a decrease of the unification scale due to a dilution of the scalar field. A lowering of Λ_G implies according to

$$\frac{\dot{\alpha}}{\alpha} = -\frac{1}{2\pi} \alpha \left(b_2^S + \frac{5}{3} b_1^S \right) \frac{\dot{\Lambda}_G}{\Lambda_G} = -0.014 \frac{\dot{\Lambda}_G}{\Lambda_G}.$$

If $\dot{\Lambda}_G/\Lambda_G$ is negative, $\dot{\alpha}/\alpha$ increases in time, consistent with the experimental observation. Taking $\Delta\alpha/\alpha = -0.72 \times 10^{-5}$, we would conclude $\Delta\Lambda_G/\Lambda_G = 5.1 \times 10^{-4}$, i.e. the scale of grand unification about 8 billion years ago was about 8.3×10^{12} GeV higher than today.

Proton Decay faster in future

Quantum Optics

(MPQ ~ Haensch, Walther)

C4

Suppose: $\dot{\alpha}/\alpha \approx -1.2 \cdot 10^{-15}$

$$\dot{\lambda}/\lambda \approx 2.4 \cdot 10^{-14} \quad (\text{ca.})$$

Cesium clock: $1s =: 6192631770$ cycles
of microwave light $\sim h\nu$ -transition of
cesium -133

$$V_{hp} \sim \frac{m_e}{\pi} \alpha^4$$

\rightarrow Cesium clock + H-clock (no dep. of λ)
(~ 3 cesium cycles / day)

1. Step: Cesium \Rightarrow H

Effect $\sim 3\sigma$, if $\dot{\lambda}/\lambda \approx 10^{-14} \text{ yr}^{-1}$

2. Step: Indium (trapped) \sim AG (trapped)

\rightarrow sensitive to $\dot{\lambda}/\lambda \approx 10^{-17} \text{ yr}^{-1}$
 $(\sim 3 \text{ yrs})$

e.g.: $\dot{\lambda}/\lambda = (2.13 \pm 0.01) \cdot 10^{-14}$ (H3)

Experiment at MPQ (Munich)

Measure absolute optical frequency
relative to cesium atomic clock
 \rightarrow F..., Haenel

486 nm dye laser in the
hydrogen spectrometer

Reference: cesium fountain clock
(Pharao) LPTF Paris

1999: Hydrogen 1S-2S frequency
accurate to $1.4 \cdot 10^{-14}$

Since February 03:
octave spanning comb synthesizer
to measure 1S-2S transition
relative to PHARAO (brought
to Munich again, no sat. exp.)

1S-2S - transition:
2 466 061 413 187 127 (18) Hz

24 (50) Hz drift in 43 months

$$\rightarrow 2.8(5.7) \cdot 10^{-15} \text{ per year (pred.)}$$

$$\text{Change of } \alpha: \sim 1 \cdot 10^{-15} \text{ per year}$$

Expected: $17 \cdot 10^{-15}$ for
hyperfine transitions
(\rightarrow PHARAO)

$$\rightarrow \text{Expect: } \sim 2 \cdot 10^{-14} \text{ (unlikely)}$$

Further tests are going on.

Resolution

Change of α today smaller?
(no linear extrapolation of
astrophysical effect!)

Possible! / Astrophysics wrong?

→ Change of α essentially stopped
say 3 bn years ago
(→ Oklo constraint)

—

Cancellation of effects:

$$\frac{\dot{\alpha}_{un}}{\alpha_{un}}, \quad \frac{\dot{\Lambda}_{un}}{\Lambda_{un}}$$

\ /

Different signs

→ cancellation (or near cancellation)

But effect should be there

at level 10^{-15} (\rightarrow further tests)

Summary ~ Conclusions

≥ 18 constants in S.M.

Possible relations among them.

Some fund. constants rather

complicated (e.g. nucleon mass)

Grand unif: relates $\alpha, \alpha_w, \alpha_s$

Time dependence of α

\rightarrow " " of α_s, α_w

Oklo constraint: questionable

$$\frac{\Delta}{\pi} \sim \pm 35 \cdot \frac{\dot{\alpha}}{\alpha}$$

\rightarrow change in cesium clocks

Exp.: frequency change

$$\leq 3 \cdot 10^{-15}$$

Expected: $\sim 2 \cdot 10^{-14}$

(problem)

Cancellation? No change of α today?