united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics
40th anniversary
1964
2004

SMR.1580 - 3

CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

FUNDAMENTAL CONSTANTS AT HIGH ENERGY
(Time Variation of QCD Scale)

Harald Fritzsch
LMU, Munich

Fundamental Constants

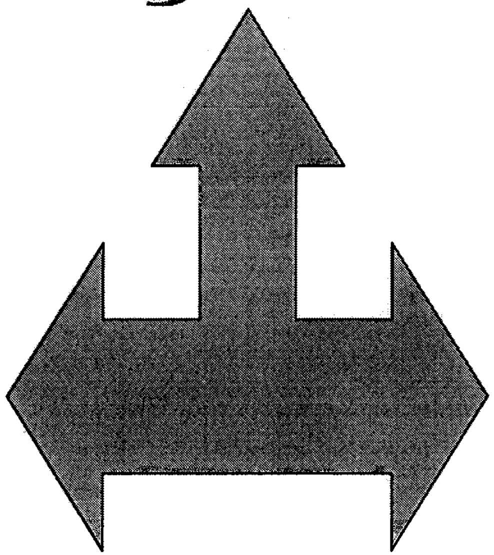
at High Energy

(Time Variation of QCD scale)

Harald Fritzsch
LMU Munich

Physics

Boundary Conditions

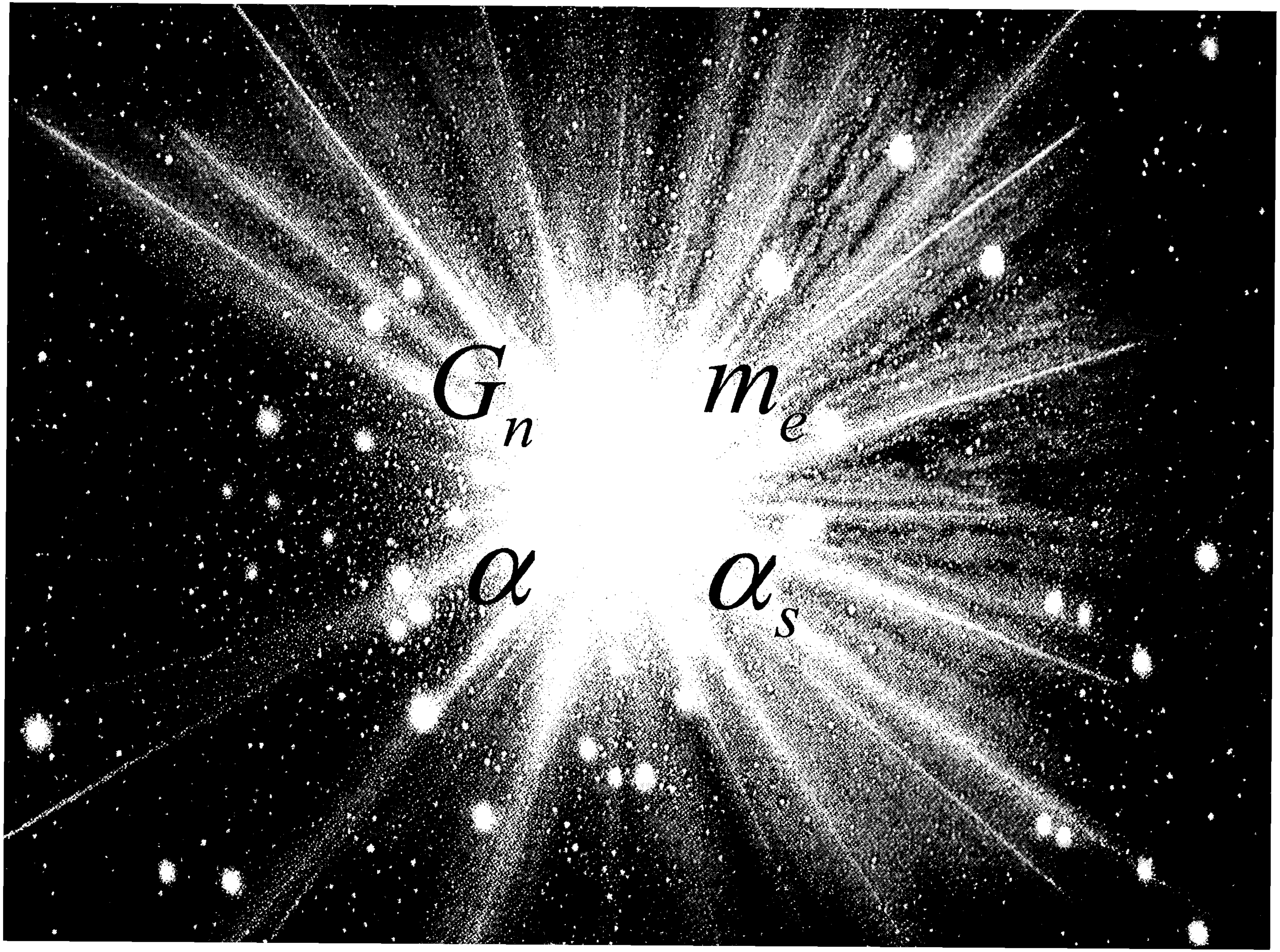


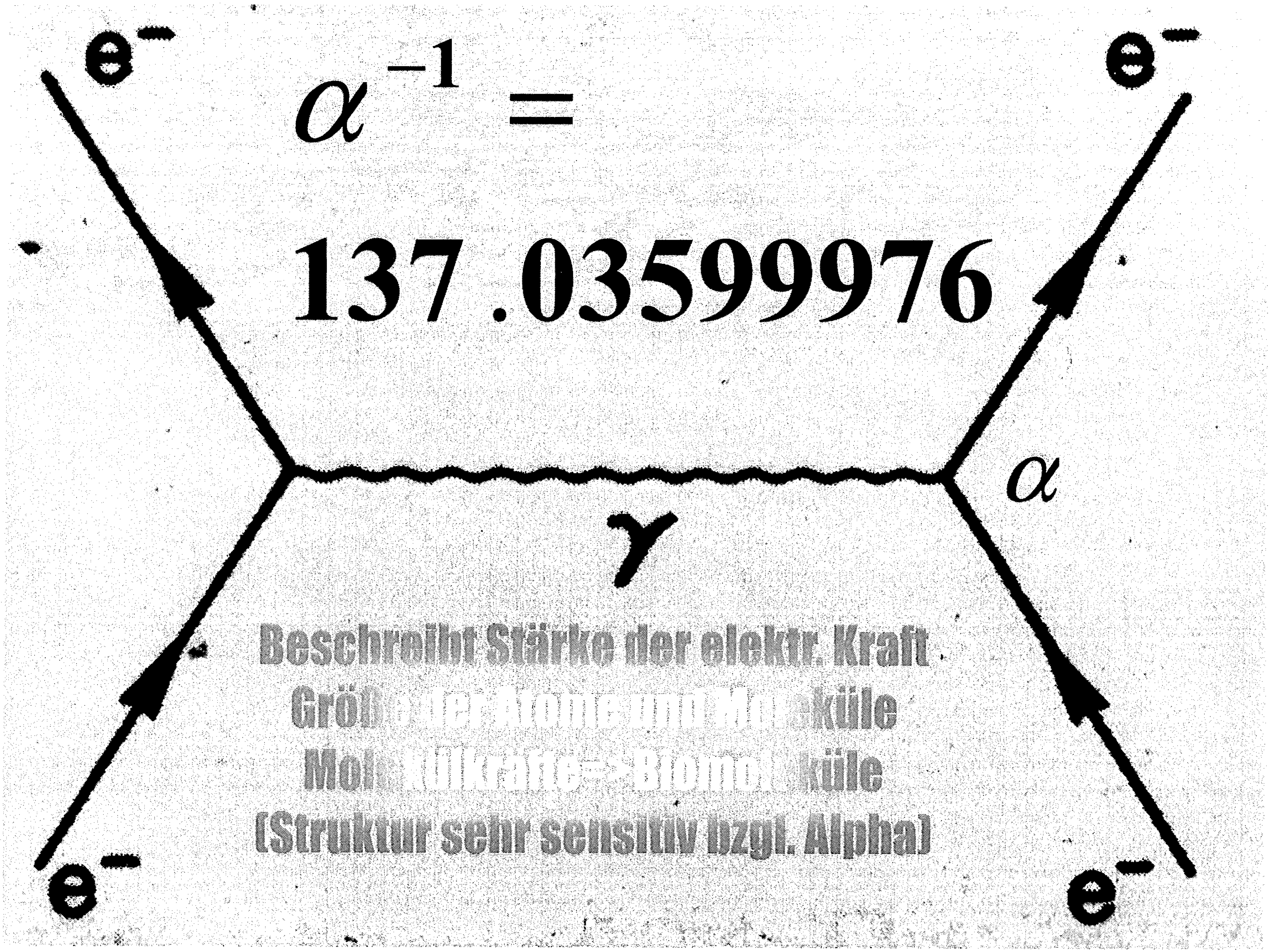
Local Laws of Nature

Role of Fundamental Constants?

What Are Fundamental Constants?

Cosmic Accidents?
Determined by Dynamics?
Changing in Time?
Given by Self-Consistency?
Calculable?


G_n
m_e
α
α_s



e⁻
e⁻
α⁻¹ =
137.03599976
α
γ
Beschreibt Stärke der elektr. Kraft
Größe der Atome und Moleküle
Molekülkräfte => Biomoleküle
(Struktur sehr sensitiv bzgl. Alpha)
e⁻
e⁻

Quantum Field Theory

$\alpha \Longrightarrow$ function of scale (energy)

Quantum–fluctuations of fields (e^+e–pairs)

e^+e^-: dipoles with size m_e^{-1}

$\rightarrow$ partial screening of bare charge of electron at distances $> m_e^{-1}$.

$$\alpha = (137, \ldots)^{-1} \rightarrow \alpha_{\text{eff}}\left(m_e^2\right)$$

$$\alpha_{\text{eff}}\left(q^2\right) = \frac{\alpha}{1 - \frac{\alpha}{3\pi}\ln\left(\frac{-q^2}{Am_e^2}\right)}$$

$$A = \exp(5/3)\,(-q^2 > 0)\,.$$

Renormalization–Group:

$$\frac{d}{d\ln(q/M)}\,\bar{e}\,(q;e_r) \;=\; \beta\,(\bar{e})$$

$$\bar{e}\,(M;e_r) \;=\; e_r$$

$$\text{QED}:\beta(e) \;=\; \frac{e^3}{12\pi^2}+0\left(e^5\right)$$

High Energy:

$$\mu^+\mu^-,\tau^+\tau^-,\bar{q}q,W^+W^-$$

$$\rightarrow\beta(e) \;=\; n_{\text{eff}}\cdot\frac{e^3}{12\pi^2}+\ldots$$

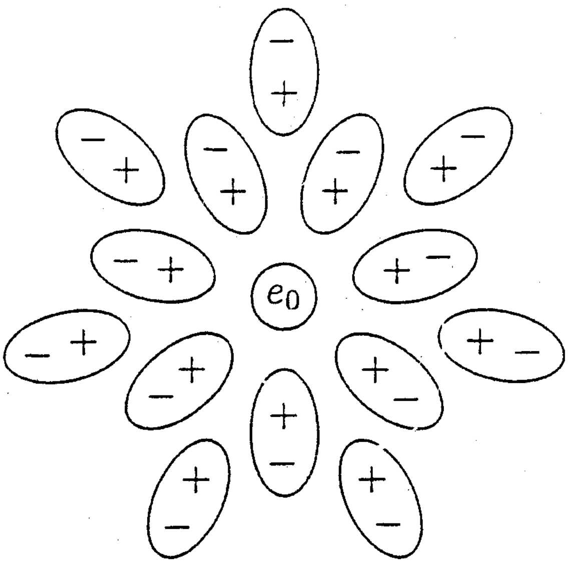
LEP:

$$\alpha(200GeV) \;\cong\; (127)^{-1}\,(\sim 10\% \;\; \text{larger})\,.$$

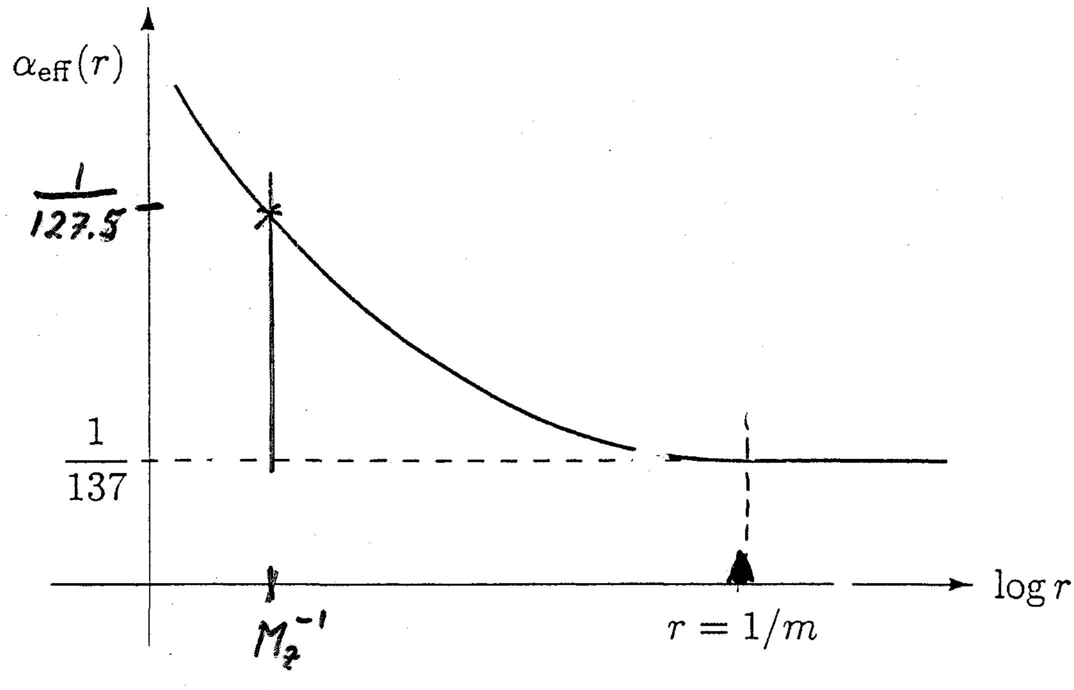
$$\alpha\,(M_Z) \;\cong\; (127.8)^{-1}$$

QED

B



Vacuum Polarization



↓

LEP, SLC

Example **Finestructure Constant** $\alpha = \frac{e^2}{\hbar c}$

→ Sommerfeld 1916

Originally it was assumed:

$$1/\alpha = 137$$

(integer!)

Philosophy and numerology:

Eddington: 137 > 136 = Nr of charged objects $\alpha^{-1} = \frac{16^2 - 16}{2} + 16 = 136$

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

Lederman: 137 Eola Road, IL

Feynman: 137

Heisenberg (~30...):

$$\alpha = 2^{-4} 3^{-3} \pi$$

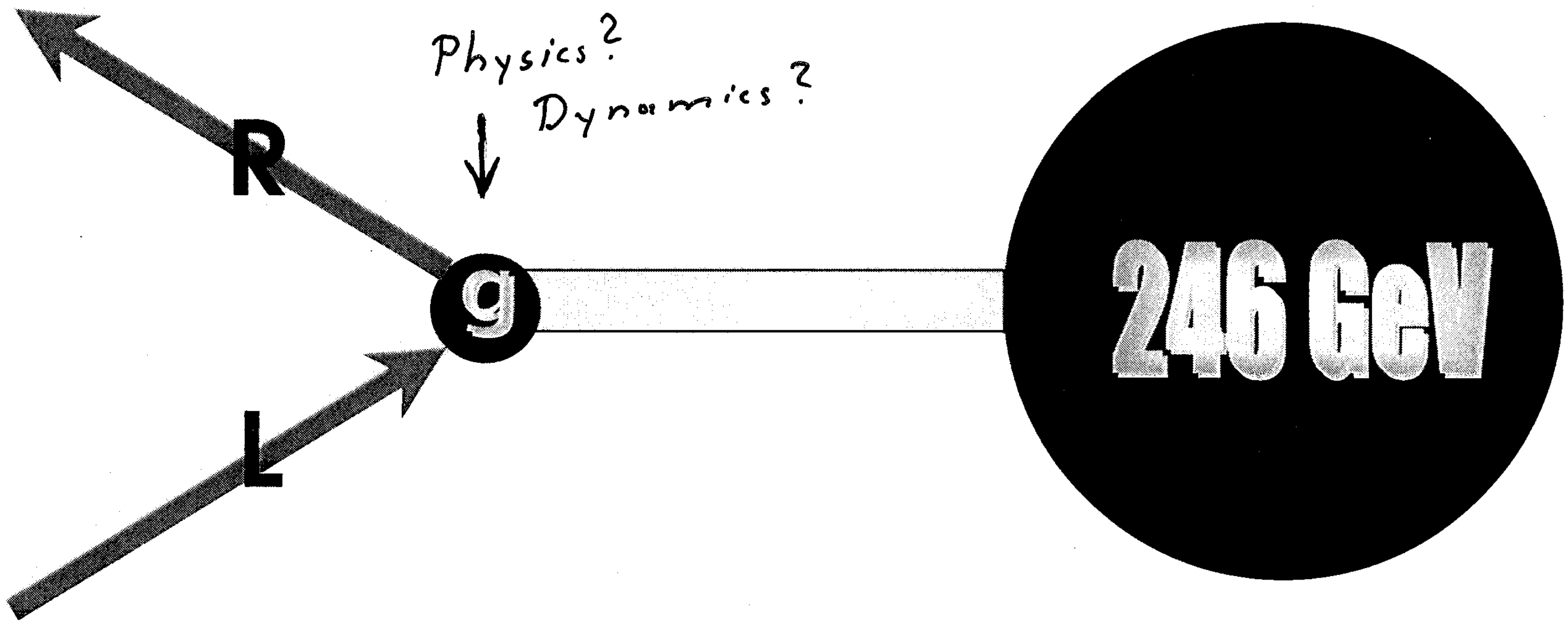
= 1/137.6...

Wyler (1971)
1ppm

$$\alpha = \frac{9}{8\pi^4}\left(\frac{\pi^5}{2^4 5!}\right)^{1/4}$$

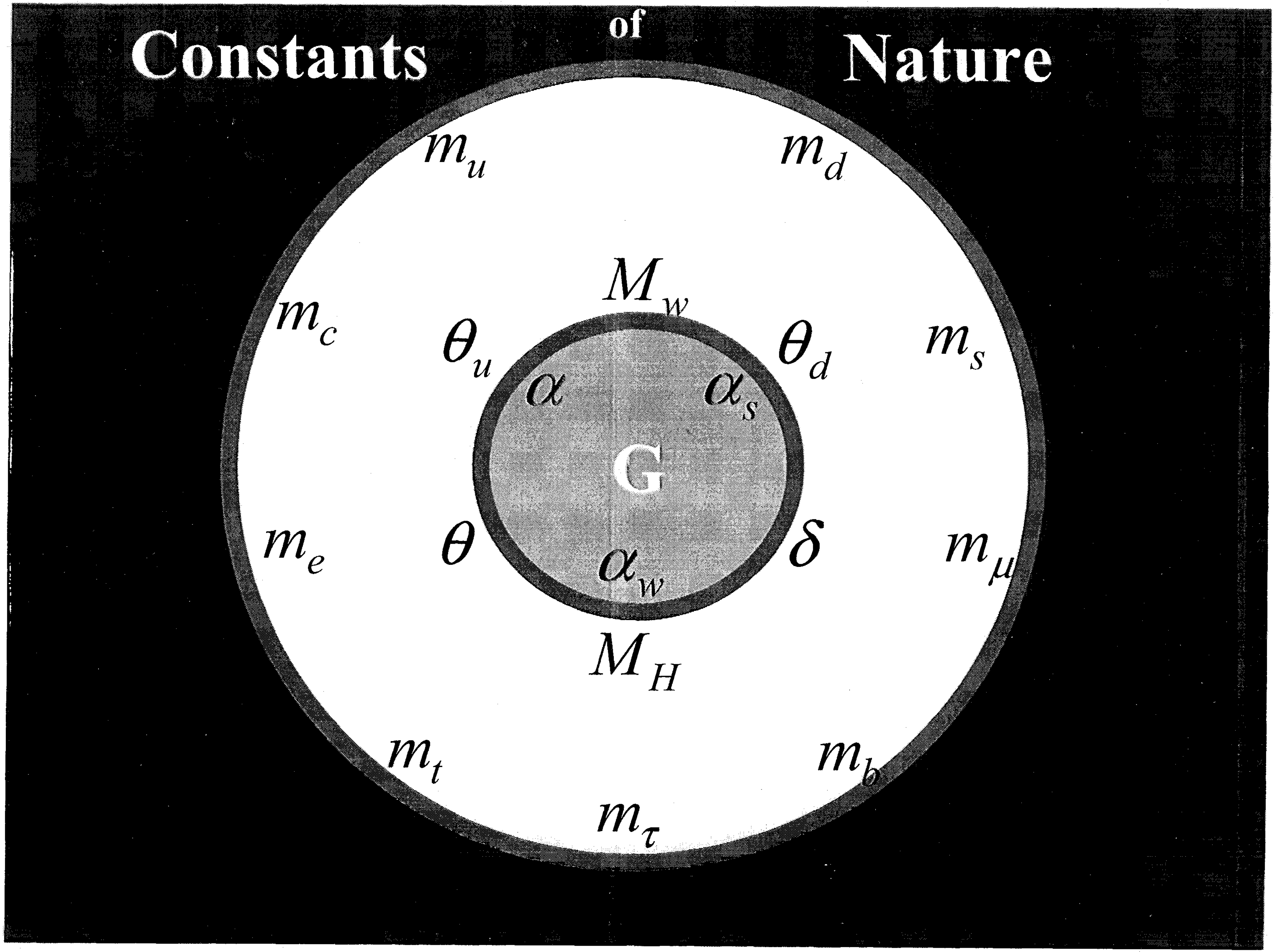
The Dark Corner of HEP ~

Fermion Masses: Arbitrary



$$m_e = \mathbf{0.511}MeV = \mathbf{0.0000021 \bullet 246}GeV = 2.000 \bullet 10^{-30}\,lb$$

$\frac{m_e}{m_p}$: 0.20 ppb accuracy (→ quantum optics)


Constants of Nature
m_u
m_d
M_w
m_c
θ_u
θ_d
m_s
α
α_s
G
m_e
θ
δ
m_μ
α_w
M_H
m_t
m_b
m_τ

Relations among constants?

e.g. flavor mixing

$$\theta_u \cong \sqrt{\frac{m_u}{m_c}} \qquad \theta_d \cong \sqrt{\frac{m_d}{m_s}}$$

$$\delta \cong 90^\circ$$

$$\theta \cong \frac{m_s}{m_b} + \frac{m_c}{m_t}$$

18 Pm. $\longrightarrow$ 14 Pm.

Cosmic time dependence of fundamental constants

H. Fritzsch   Munich

→ CERN-Courier March 03
Eur. Journals, Phys. Today

Keck telescope (Australia, England, US)

"many multiplet method"   (Webb, Wolfe...

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

~150 quasars (→ 11 bn years in time)

$$\frac{\Delta\alpha}{\alpha} = \underset{(-0.54 \pm 0.12)}{(-0.72 \pm 0.18)} \cdot 10^{-5}$$

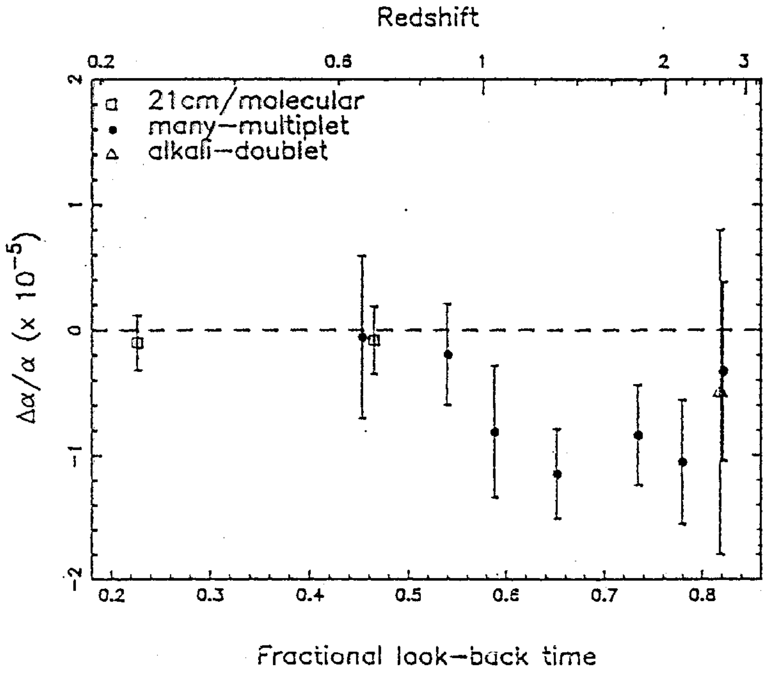
α = 1 / 137,036 99976   (today)

early $\alpha \approx 1 / 137,037$ (... 036)

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

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

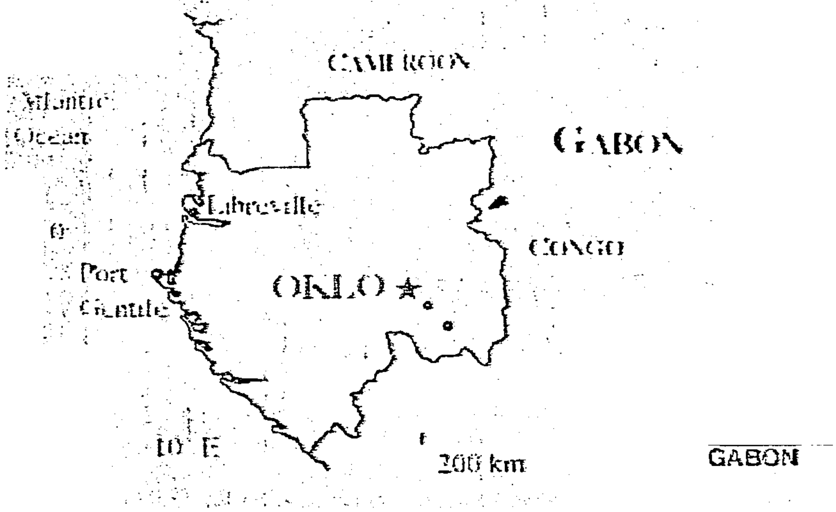
TABLE I: Summary of results for 4 independent samples. Values of $\Delta\alpha/\alpha$ are weighted means in units of 10^{-5}. MM and AD indicate "many-multiplet" and "alkali-doublet". N_{abs} is the number of absorption systems in each sample.



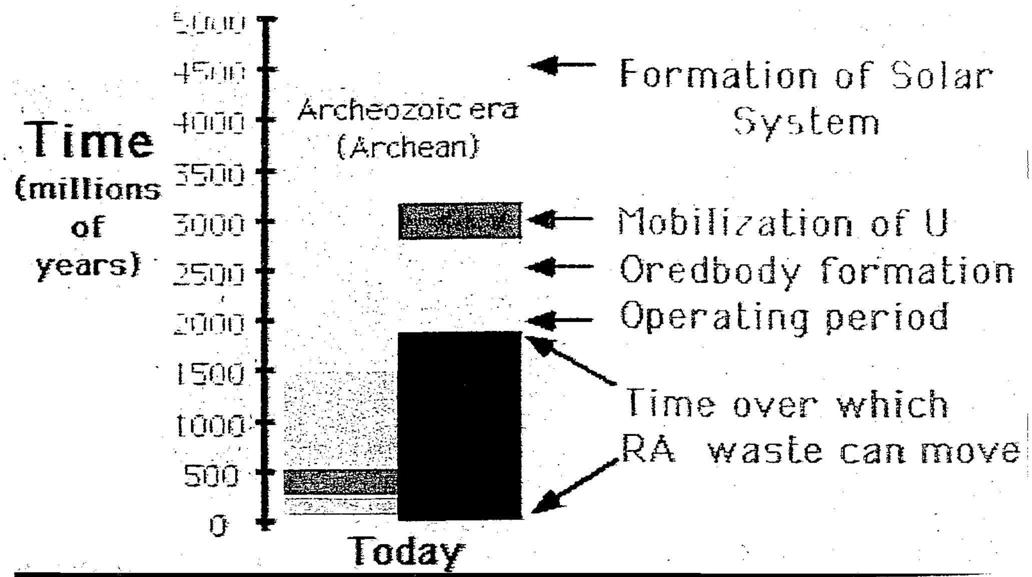
13.9 Gyr

FIG. 1: $\Delta\alpha/\alpha$ vs. fractional look-back time to the Big Bang. The conversion between redshift and look-back time assumes $H_0 = 68$ 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_p, 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, SiII) [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].

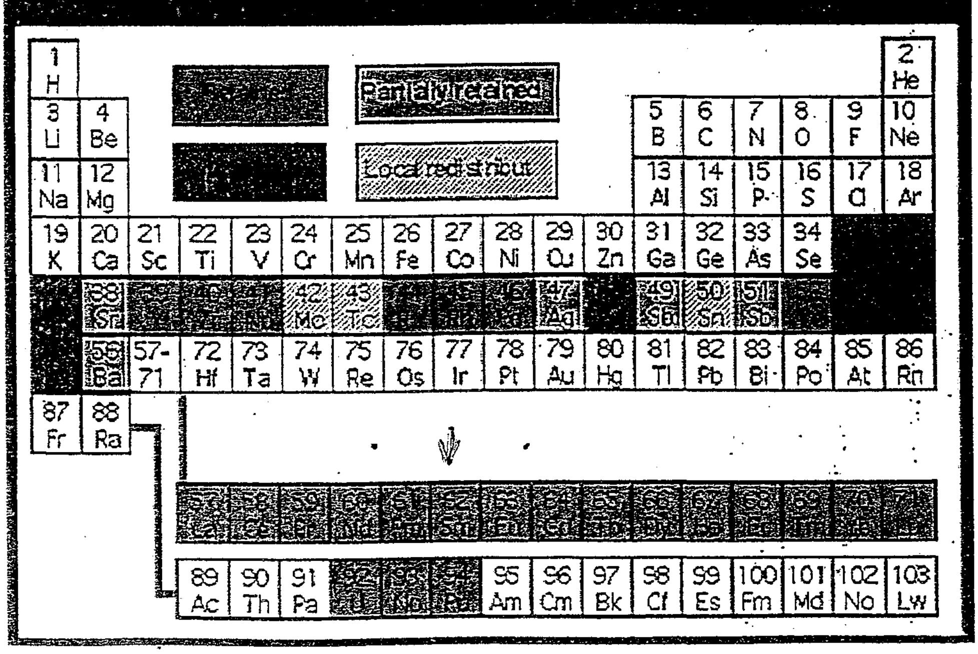
Oklo: Location



Oklo Time Scales



Retention of Fission Products at OKLO



The Oklo Phenomenon

1.8 billion years back

River Oklo

Gabon, W-Africa

Natural reactor

High concentration of U

Natural enrichment of U235
(3% about 2bn yrs. ago, 0.7% today)

Low concentration of n absorbers

Critical size

Moderator (25% C, 75% Water)

Not commissioned by DOE ~ NRC

but operated for ~ 100 Mio years.

Strong n-absorbers found only in small quantities → reactor activity

Sm^{149} Eu^{151}, GD^{155}, Gd^{152}

Shlyakhter (Шляктр)

→ **Damour, Dyson (96)**

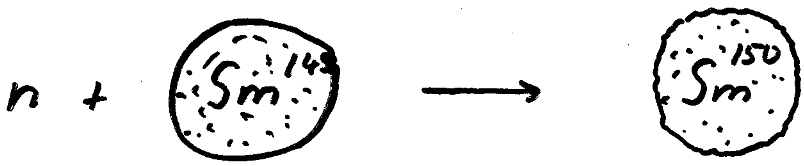
Neutron capture

$$Sm^{149} + \boldsymbol{n} \rightarrow Sm^{150} + \gamma$$

thermal x-section

D.D.: $57\ \text{kb} \leq \hat{\sigma}_{149} \leq 93\ \text{kb}$

Large x-section: resonance just above threshold



E = <u>0.0973</u> eV

Resonance position:

affects strongly x-section

time shift?

$$\Delta = E_r(Oklo) - E_r\ \text{(now)}$$

$$-0.12\ \text{eV} < \Delta < 0.09\ \text{eV}$$

$$\mathrm{H} = \mathrm{H}^{\mathrm{nucl}} + \mathrm{H}^{\mathrm{elm}}$$

$$\downarrow$$

$$e^2 \sum_{a,b} r_{ab}^{-1} \qquad \text{(Coulomb)}$$

$$\rightarrow \alpha \cdot \frac{dE_r}{d\alpha} < -(1{,}09 \pm 0.09)\ \text{MeV}$$

Bethe-Weizsächer: -1.14 MeV

$$-0.9 \bullet 10^{-7} < \frac{\alpha(Oklo) - \alpha(now)}{\alpha} < 1.2 \bullet 10^{-7}$$

Oklo

Natural reactor in Gabon (Africa)

Investigated since ~1970 by French physicists. (Active: ~2 bn years ago)

Samarium: decay depends strongly on nuclear resonance

Resonance position cannot have changed much

Dyson–Damour: $\frac{\dot{\alpha}}{\alpha} < 10^{-16}$ (10^{-17})

(if no other pms. change)

→ Problem with astrophysics

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

→ Oklo constraint questionable

Change of α:

$M_n - M_p$ affected

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

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

$M_n - M_p \nearrow$ ($\rightarrow$ nucleosynthesis)

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

$g \qquad g'$

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

G_F affected ($\rightarrow$ nucleosynthesis)

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

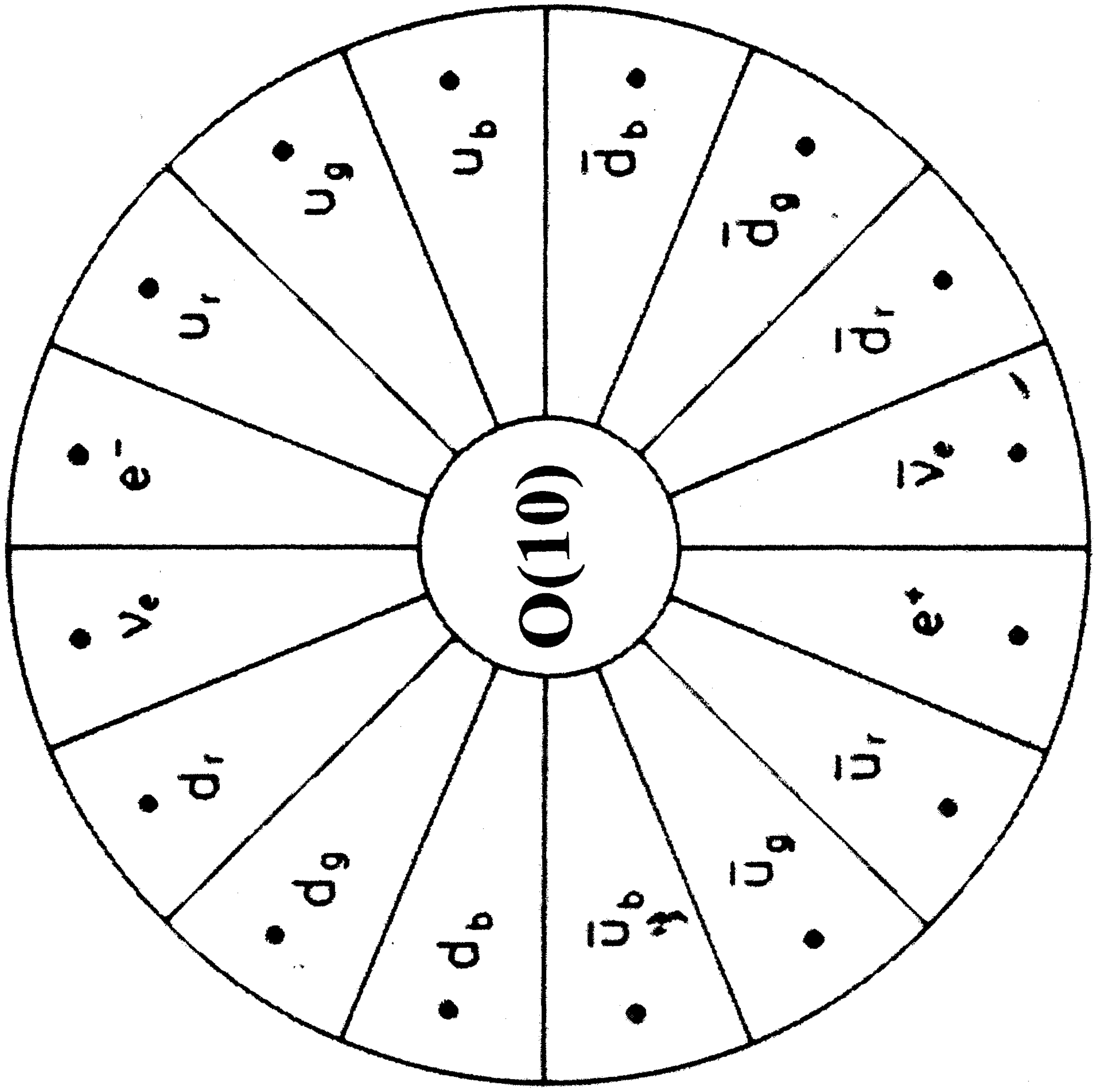
$\tilde{g}$

$\rightarrow \tilde{g}$ affected

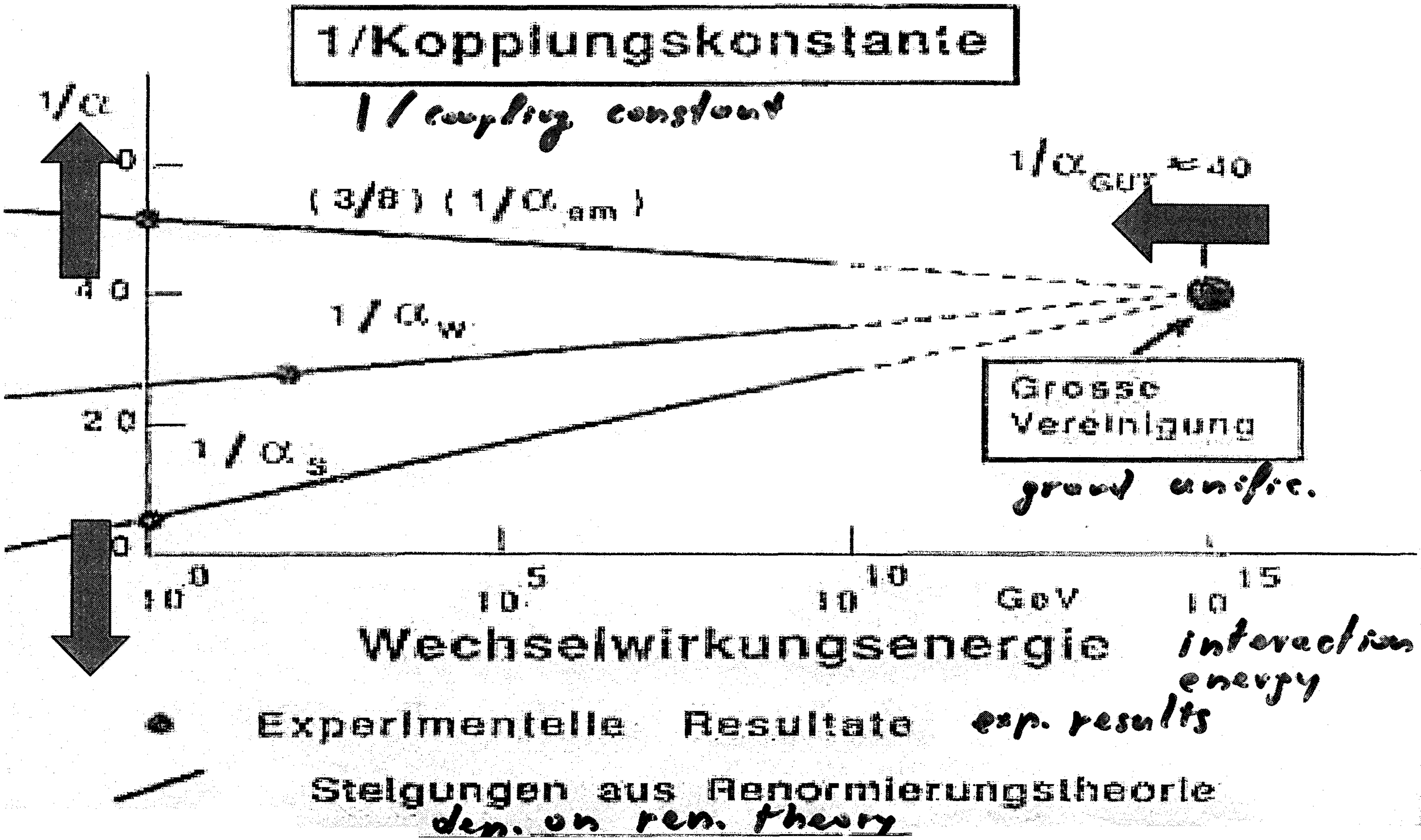
$\rightarrow g_s$ affected (Λ_c)

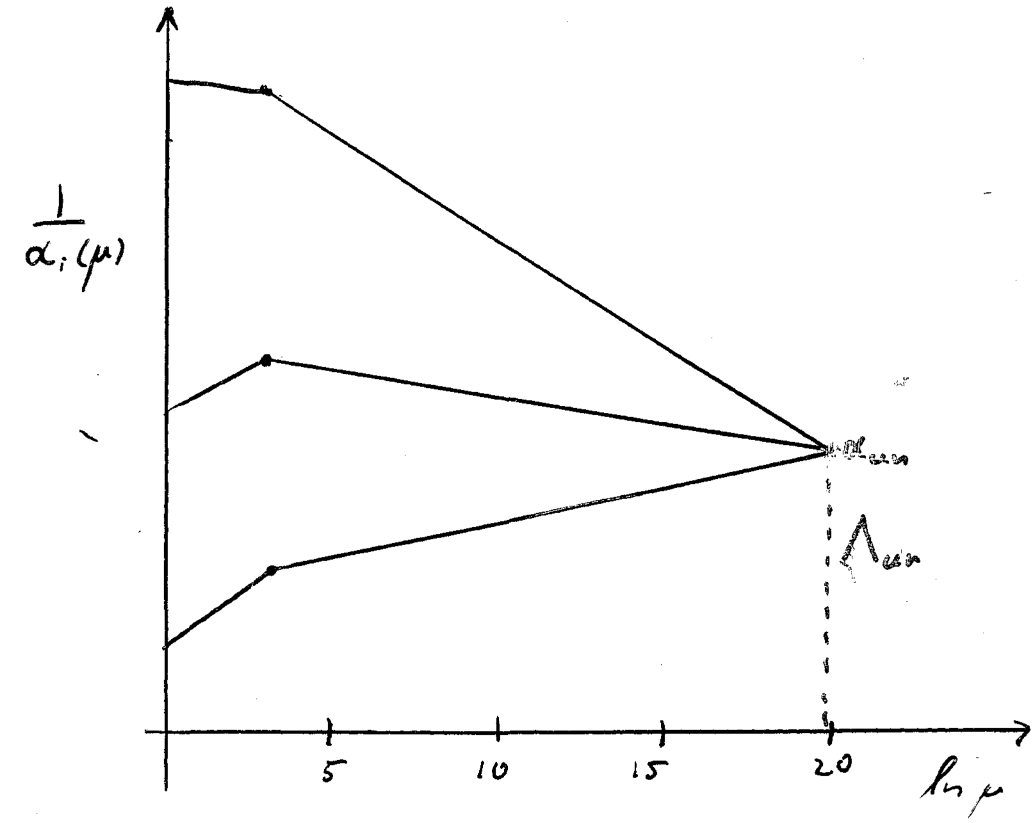
$\rightarrow M_p \searrow$

Systematic analysis needed!



Vereinheitlichung aller Kräfte


1/Kopplungskonstante
1/coupling constant
1/α
40
20
0
(3/8) (1/α_em)
1/α_W
1/α_S
1/α_GUT ≈ 40
Grosse Vereinigung
grand unific.
10^0
10^5
10^10
GeV
10^15
Wechselwirkungsenergie
interaction energy
Experimentelle Resultate
exp. results
Steigungen aus Renormierungstheorie
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}

Calmet, F.
Langacker, Segre, Strassl
Nir...

In general:

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

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

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

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

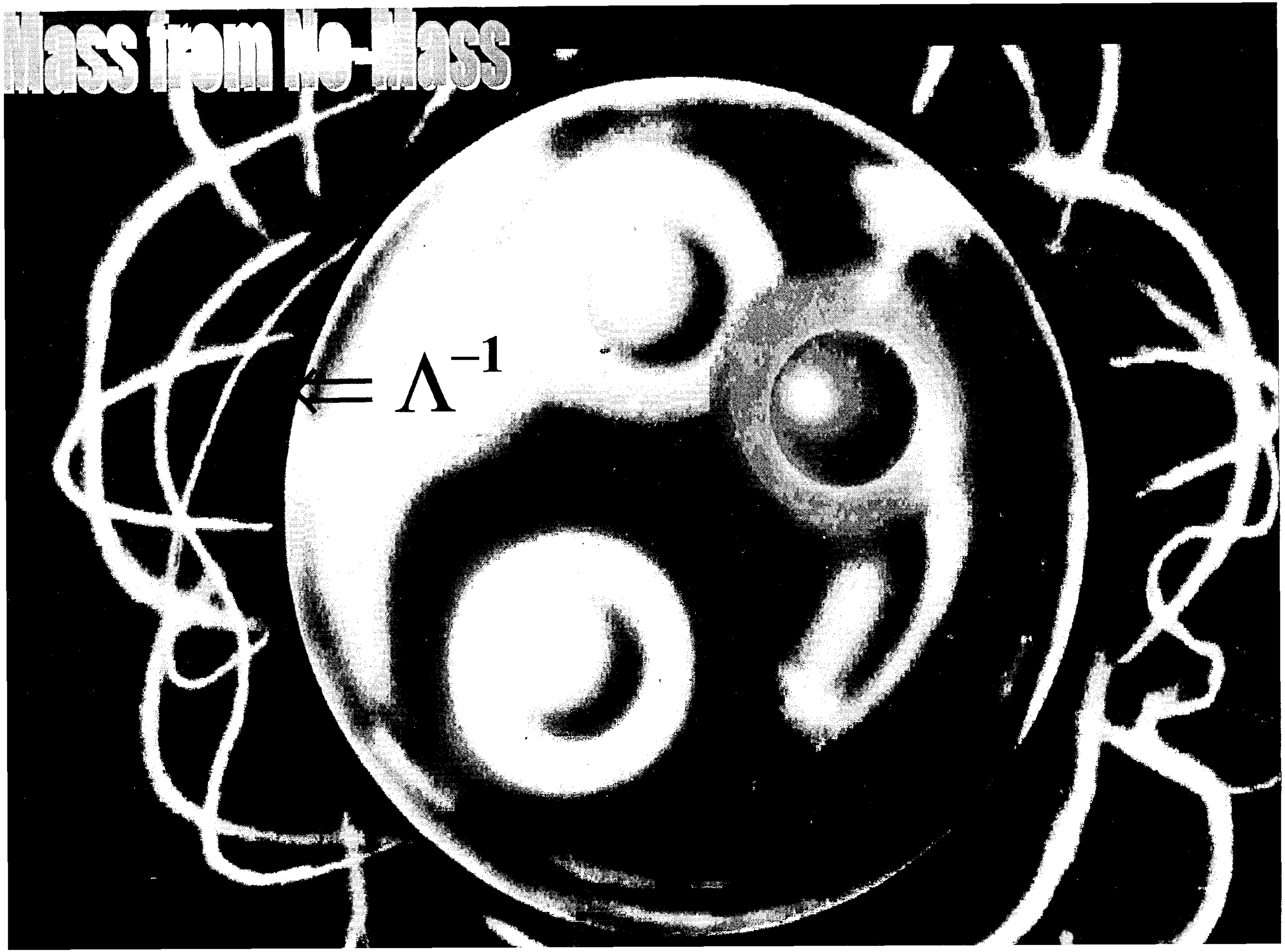
→ Magnetic Moments of Nuclei:

$$\frac{\dot{\mu}_p}{\mu_p} = \frac{\dot{\mu}_N}{\mu_N} \approx -38,8\,\frac{\dot{\alpha}}{\alpha} \sim 3.9 \cdot 10^{-14}/\text{year}$$

α_{un} invariant, change of Λ_{un}:

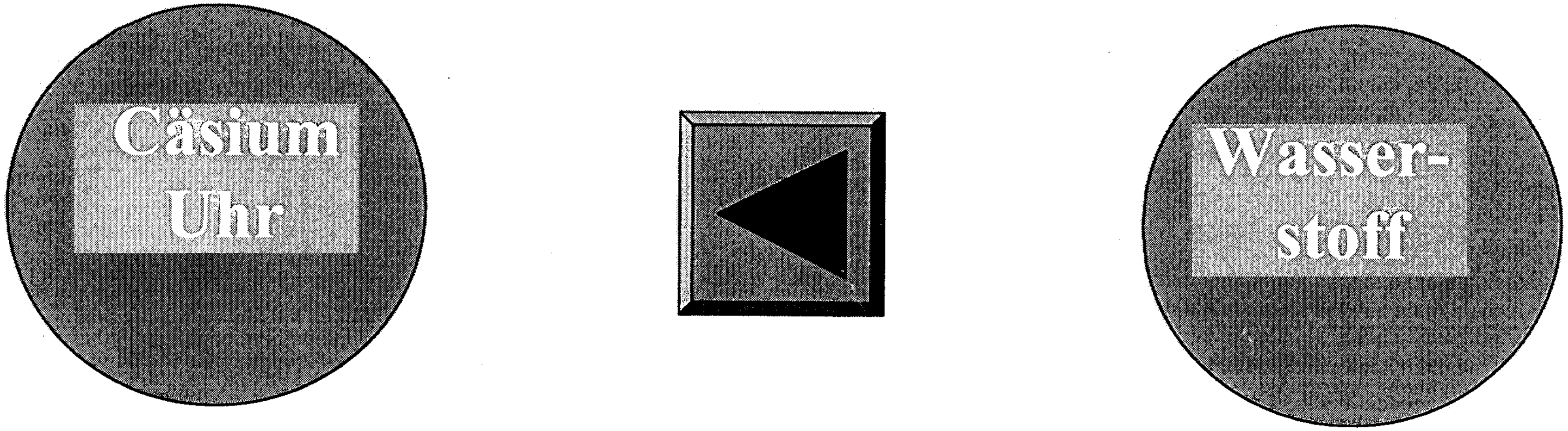
$$\frac{\dot{\Lambda}}{\Lambda} \approx -31 \cdot \frac{\dot{\alpha}}{\alpha}$$

(sign change!)


Mass from No-Mass
$\Leftarrow \Lambda^{-1}$

Vergleich

Comparison



Cs-clock

H

Unterschied ca. 3 Cäsiumschwingungen

3 Cs-oscillations / day

pro Tag

Experimente am MPQ Garching und IST Boulder, USA

IST

Quantum Optics

(MPQ ~ Haensch, Walther) C4

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

$\dot{\Lambda}/\Lambda \cong 2.4 \cdot 10^{-14}$ (ex.)

Cesium clock: 1 s =: 6192631770 cycles of microwave light ~ hf-transition of cesium-133

$\nu_{hf} \sim \frac{m_e}{\Lambda} \alpha^4$

→ Cesium clock ≠ H-clock (no dep. of Λ)

(~ 3 cesium cycles / day)

1. Step: Cesium ⟷ H

Effect ~ 3σ, if $\frac{\dot{\Lambda}}{\Lambda} \approx 10^{-14}$ yr^{-1}

2. Step: Indium (trapped) ~ AG (trapped)

→ sensitive to $\frac{\dot{\Lambda}}{\Lambda} \approx 10^{-17}$ yr^{-1} (~ 3 yrs)

e.g.: $\dot{\Lambda}/\Lambda = (2.13 \pm 0.01) \cdot 10^{-14}$ (43

Experiment at MPQ (Munich)

Measure absolute optical frequency relative to cesium atomic clock
(→ F. ..., Haens

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,

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

($\sim 10^{-14}$ acc.!)

24 (50) Hz drift in 43 months

−0.9 (2.9)

→ ~~2.8~~ (~~5.7~~) · 10^{-15} per year

(prel.)

Change of α: ~ 10^{-15}/yr

→ expect: $2 \cdot 10^{-14}$ for hyperfine transitions

(unlikely)

Further tests are going on.

(→ Boulder)

Partial cancellation of effect?

(vary α_{un} + Λ_{un} !)

At level ... × 10^{-15} effects should be seen!

Or: Astrophysics wrong?

New exp.: no effect! (R[illegible])

$$\frac{8}{3}\,\frac{1}{\alpha_s}\cdot\frac{\dot{\alpha}_s}{\alpha_s} = \frac{1}{\alpha}\,\frac{\dot{\alpha}}{\alpha} + \frac{1}{2\pi}(\dots)\,\frac{\dot{\Lambda}_{Gut}}{\Lambda_{Gut}}$$

partial cancellations
(s. s. th)

$$\frac{\dot{\Lambda}}{\Lambda} \sim 5\cdot\frac{\dot{\alpha}}{\alpha}$$

$\rightarrow \quad \sim 5\cdot 10^{-15}\,/\,\mathrm{yr}$

in Hänsch exp. (?)

indications for
effect of $\sim 4\cdot 10^{-15}/\mathrm{yr}$

Summary ~ Conclusions

$\geq$ 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

→ " " of α_s, α_w

Oklo constraint: questionable

$$\frac{\dot{\Lambda}}{\Lambda} \sim \pm 35 \cdot \frac{\dot{\alpha}}{\alpha}$$

→ 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?