Fundamental Constants

at High Energy

and their time dependence

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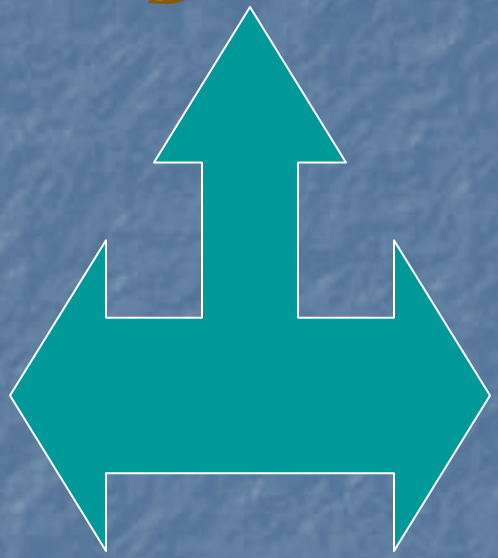
Physics



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

Example

Finestructure Constant

Sommerfeld, 1916.....

$$1 / \alpha = 137$$

Pauli (1958): Nr 137, Zürich.....

L Lederman, 137 Eola Road

Feynman: 137–how little we know

W. Heisenberg (~30...):

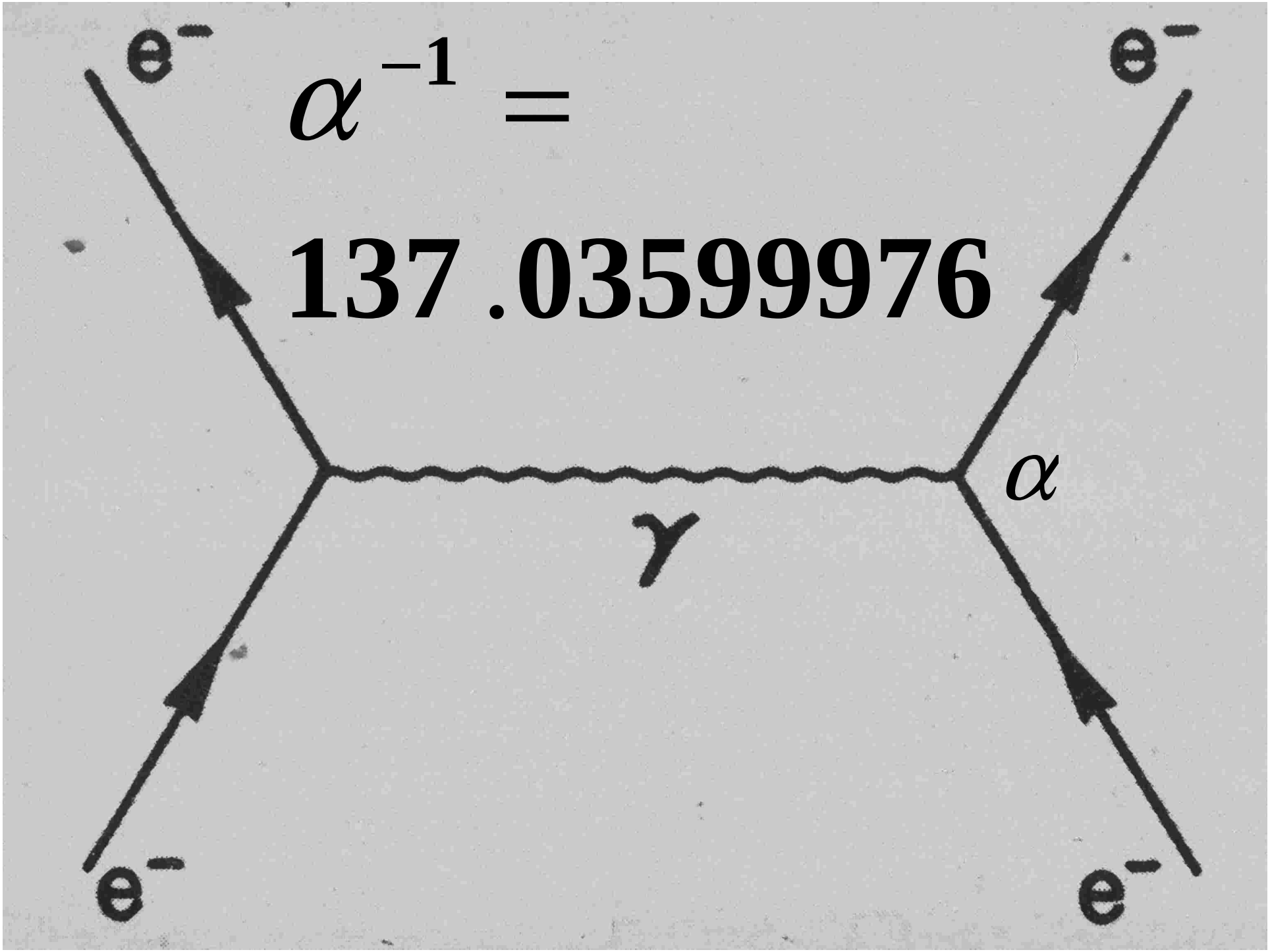
$$\alpha = 2^{-4} 3^{-3} \pi$$

= 1/137.6...

A. Wyler (1971)
1ppm

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

ratio of two group spaces


$\alpha^{-1} =$
137 .03599976
e⁻
e⁻
e⁻
e⁻
γ
α

QED: Most successful theory in science. Merging of electrodynamics, quantum mechanics and special relativity.
Renormalizable theory, tested up to 1:10 000 000
(Lamb shift, hyperfine splitting, magnetic moments)

Not expected by those, who created the theory: Dirac, Heisenberg, Pauli, ...

Quantum Field Theory:

Finestructure constant becomes function of energy or scale due to quantum fluctuations of electron-positron pairs

=> partial screening of bare charge of the electron at distances less than the compton wavelength of the electron

Renormalization Group Contribution of electron-positron pairs

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

QED

$$\beta(e)=\frac{e^3}{12\pi^2}+\ldots$$

Include:
Myons, Tauons, Quarks

$$\beta(e) = \frac{e^3}{12\pi^2}(el. + myons + tauons + u + d + s + c + b)$$

$$\alpha(200GeV)$$

LEP: $\sim 1/127$

$$\alpha(M_Z) = 1/127.8$$

Oklo Phenomen

About 1.8 billion years ago, in Gabon, Westafrika.

Natural Reactor, which operated about 100 million years.

High concentration of uranium

3% U 235 at that time (today 0.7 %)

Moderator: water from river Oklo

Not commissioned by DOE.

Discovered in the 1970ties by french nuclear physicists

It was found:

Uranium 235 had 0.717 %-

Normally: 0.720 %

=> further investigation

Shlyakhter, Dyson and Damour (1996)

Neutron Capture

Sm(149) + n =>Sm(150) + gamma

Calculation: cross section about 57 … 93 kb

very large cross section due to nuclear resonance just above threshold

E=0.0973 eV

Resonance position cannot have changed much

Change less than 0.1 eV =>

alpha(Oklo)-alpha(now)/alpha

<1/10 000 000

Change of alpha per year must be less than 1/10 000 000 000 000 000 per year (if no other parameters change) =>constraint questionable

Masses:

Where do they come from?

What is mass?

Thus far only one mechanism of mass generation established:

QCD

Mass from „no-mass“ (dimensional transmutation)

„Anti-screening“ of color – infrared slavery


Mass from no-mass
1/lambda

Experiments:

Λ_c :about 250 MeV

Mass: confined field energy

Mass in QCD is fully understood
(not, however, the quark masses)

Nucleon Mass in limit of vanishing quark masses:

$$M = const. \bullet \Lambda_c$$

const. calculable, but large errors at present.

Exp: 938.272 MeV

$$M_n = c\Lambda + c_u m_u + c_d m_d + c_s m_s + c_{elm}\Lambda$$

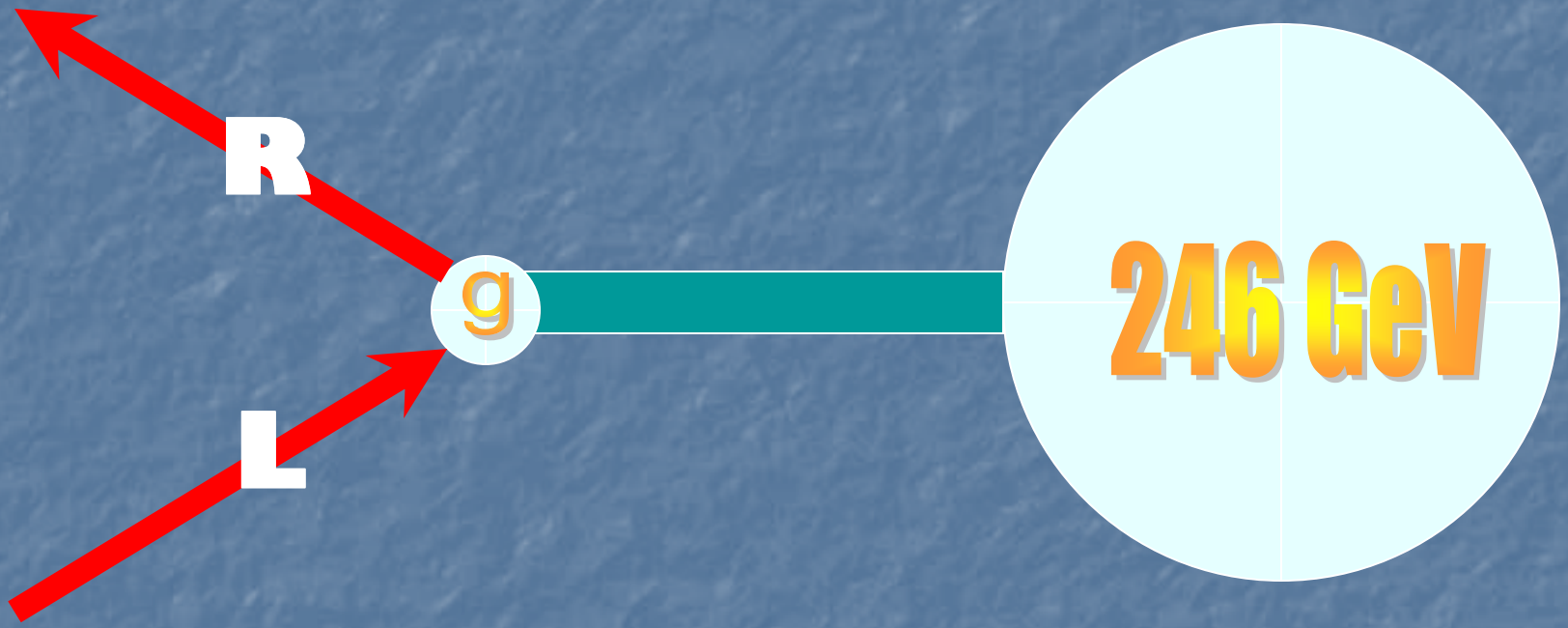
Nucleon Mass in QCD:

Nuleon mass: QCD mass and mass contributions from the quark masses

Example: QCD u d s+c QED)

$$M_p = 938.272 MeV = (861.532 + 20.138 + 19.253 + 35.362 + 1.987) MeV$$

The Dark Corner of HEP
Fermion Masses: Arbitrary



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

Sam Nunn

5 Constants for stable matter

QED

α

m_e

m_u

m_d

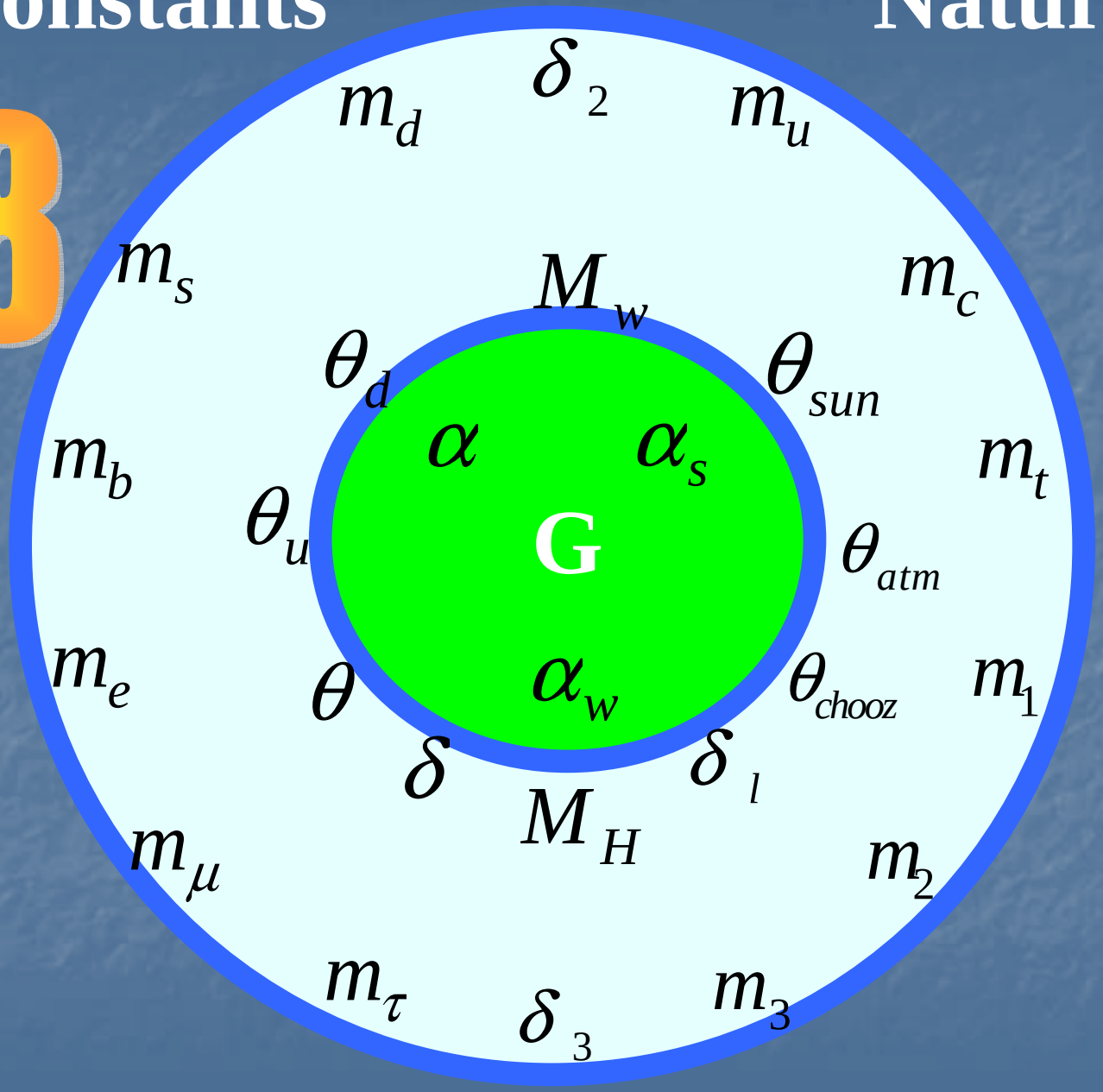
QCD

Λ

➔ Atoms, Nuclei

Constants of Nature

28



Charged leptons and quarks: (MeV)

electron: 0.51 muon: 105.7 tau: 1 777

u: 5.3 c: 1 100 t: 174 000

d: 7.8 s: 170 b: 4 500

(quark masses at 1 GeV)

m(electron) / m(mu)= m(u) / m(c) ?!

207 207

Quark Masses:

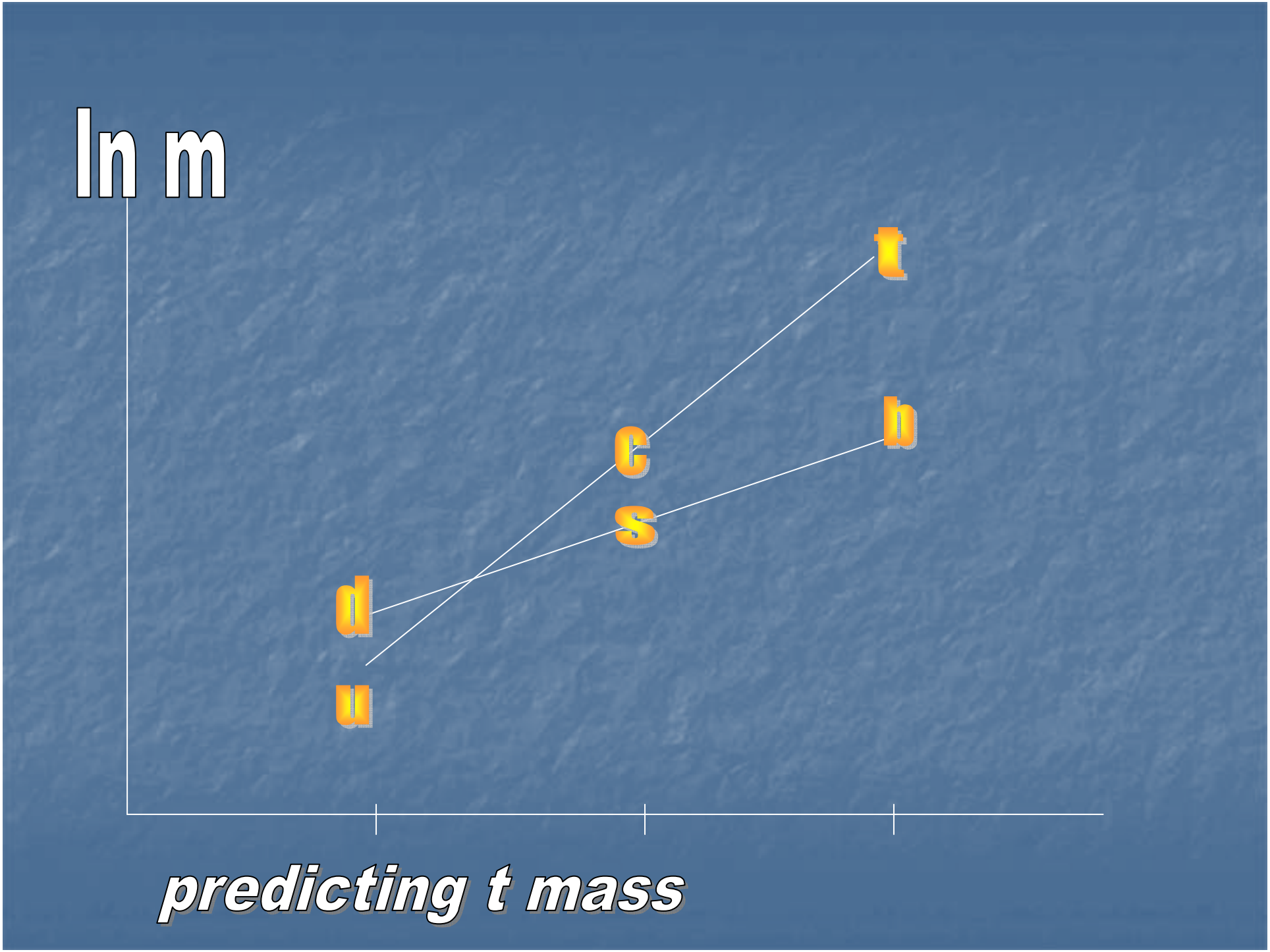
- Observed:

$$m(c) : m(t) = m(u):m(c)$$

$$1/185 \qquad 1/190$$

$$m(s):m(b) = m(d):m(s)$$

$$1/24 \qquad 1/23$$


ln m
t
b
c
s
d
u
predicting t mass

Relations among constants?

e.g. flavor mixing

(slight reduction of nr. of parameters)

$$\theta_u = \sqrt{m_u} / \sqrt{m_c}$$

$$\theta_d = \sqrt{m_d} / \sqrt{m_s}$$

similar relations for neutrino masses and mixing angles

Higgs" v.e.v.

v = 246 GeV

(Fermi constant)

$$v/\sqrt{2} \approx 174 = m_t \ ?$$

accident or due to a symmetry?

Time Variation of fundamental constants: Dirac (~1930)

Time Variation of Newtons constant G

of order 10^{-10} **per year**

(only recently excluded)

Time Variation of alpha?

Observation of fine structure of atomic levels

Quasars 5-7 billion years back

Experiment at Keck telescope (Australia, England, USA) (Webb, Wolfe)

Fine structure of Fe, Ni, Mg, Sn, A

Quasars, back to 11 bn years in time

(challenged by Reimers, Chile, investigating only one quasar)

$$\Delta\alpha/\alpha = (-0.54 \pm 0.12)10^{-5}$$

$$Linear\_App.: d\alpha/dt : \alpha \approx 1.2 \bullet 10^{-15}\ \_\ per\_year$$

Problem with Oklo

invalid, since other paramteres change too

Grand Unification

$SU(3)xSU(2)xU(1) < SU(5)$

(G, G: 1974)

$SU(3)xSU(2)xU(1) < SO(10)$

(F-M, G : 1975)

Grand unification

3 coupling constants

elm., weak and strong int.

reduced to two parameters:

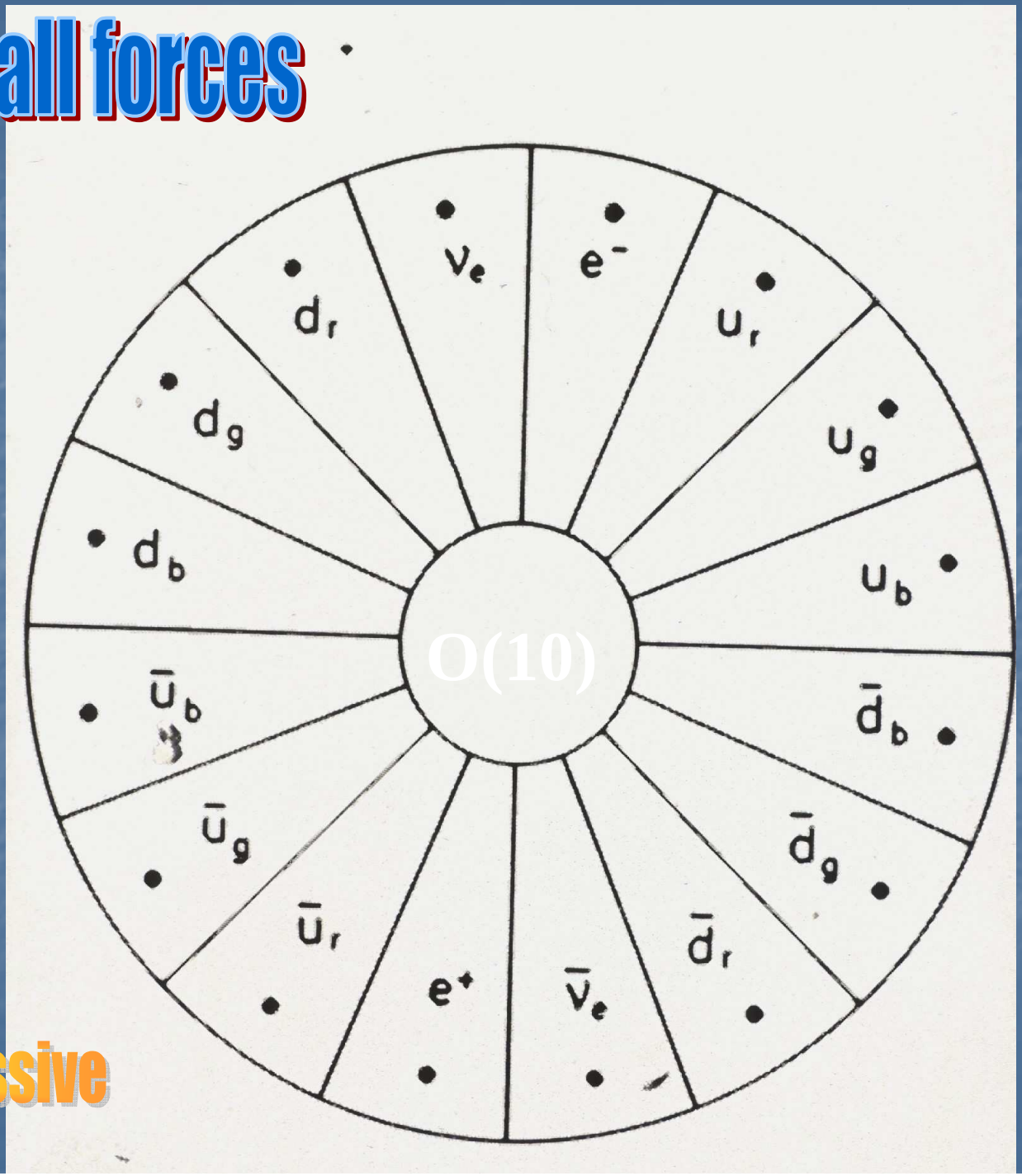
unif. scale and unified coupling

(one constant less)

Fermions in 16-plet

(incl. righthanded neutrinos)

Unification of all forces



Neutrinos are massive

In SO(10):

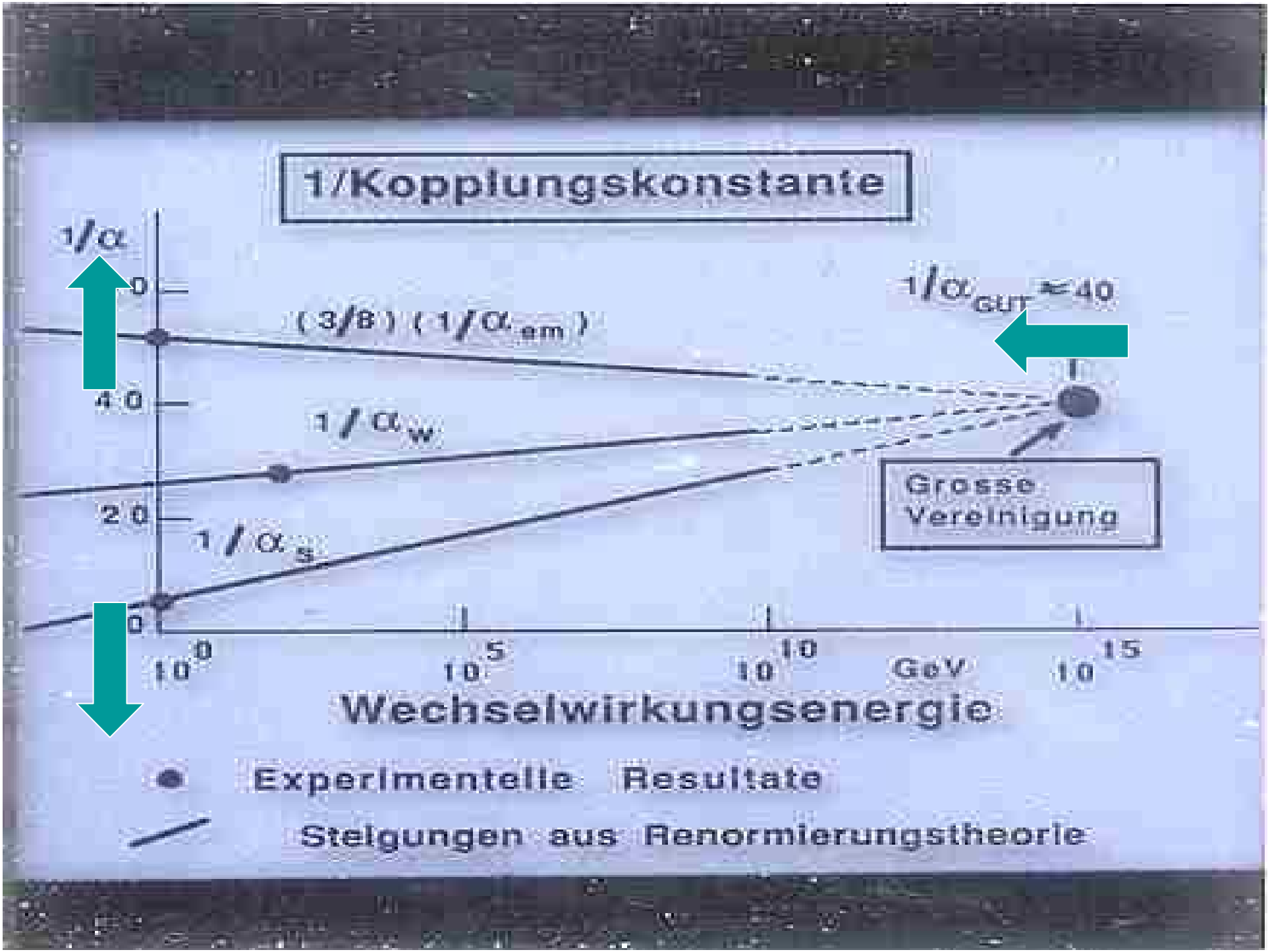
lefthanded and righthanded neutrinos

Electroweak theory:

$$SU(2)_L \times SU(2)_R \times U(1)$$

U(1): (B-L)

New energy scale for righthanded SU(2)


1/Kopplungskonstante
1/α
60
40
20
0
(3/8) (1/α em)
1/α GUT ≈40
1/α W
1/α S
Grosse Vereinigung
10 0
10 5
10 10
GeV
10 15
Wechselwirkungsenergie
Experimentelle Resultate
Steigungen aus Renormierungstheorie

$$d\alpha / dt : \alpha^2 = \frac{8}{3} d\alpha_s : \alpha_s^2 - \frac{1}{2\pi} (const.) \_ d\Lambda_{Gut} / dt : \Lambda_{Gut}$$

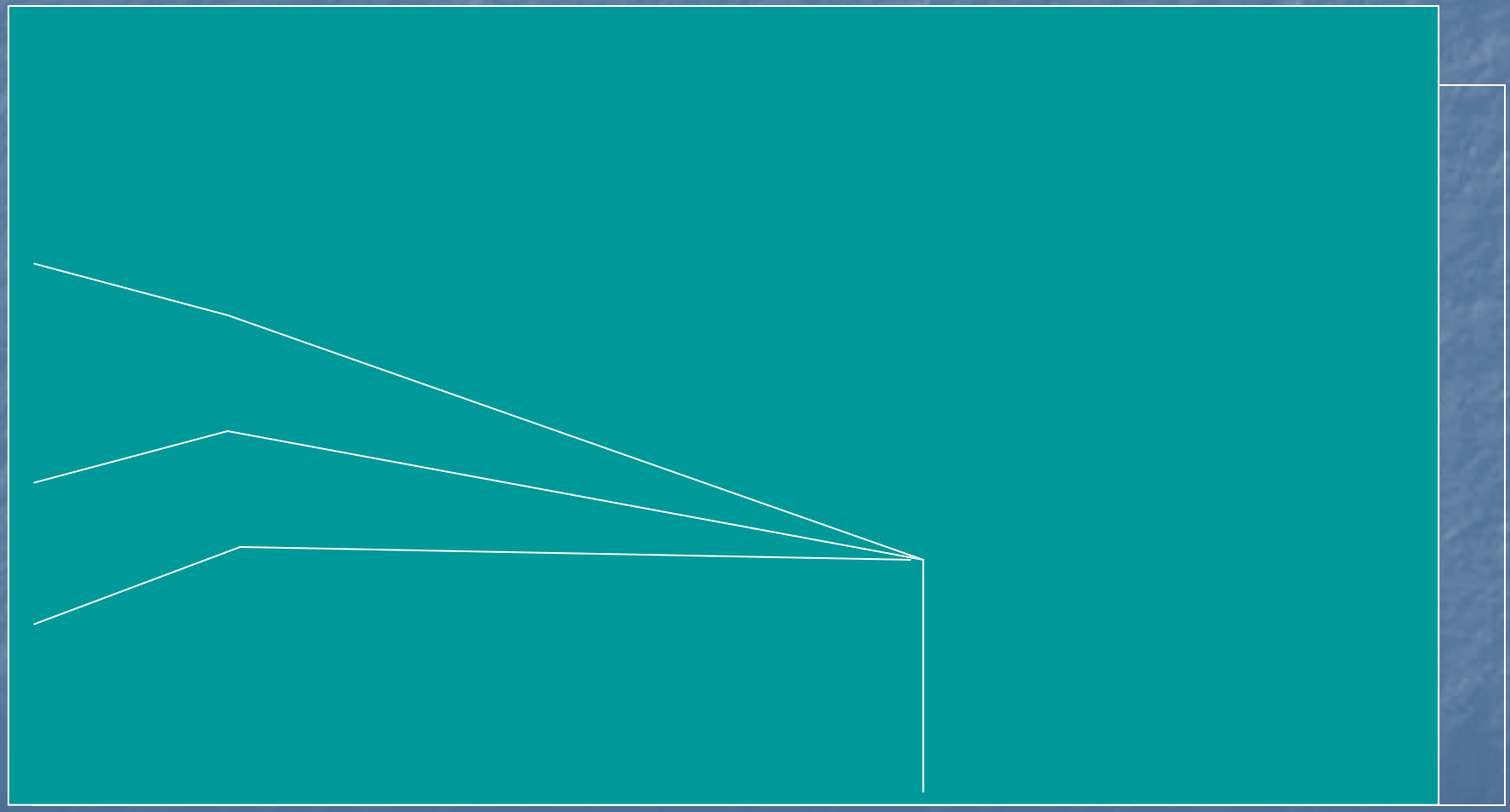
Calmet, F. - Langacker, Segre (2002)

If the scale of unification does not change, one finds:

$$d\alpha / dt : \alpha^2 = \frac{8}{3} d\alpha_s / dt : \alpha_s^2$$

Coupling Constants in SU(5) with Supersymmetry

(similar in SO(10) – Theory)



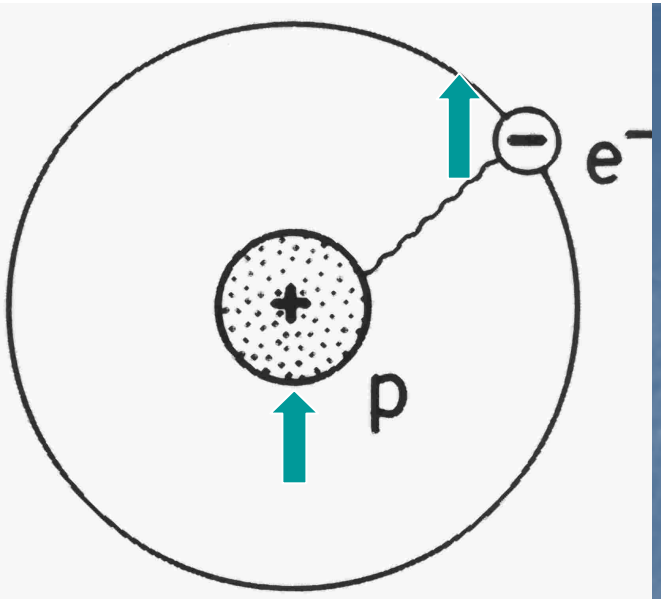
$$d\Lambda / dt : \Lambda \approx 38,8 \_ d\alpha / dt : \alpha$$

Magnetic moments of atomic nuclei would change accordingly, per year

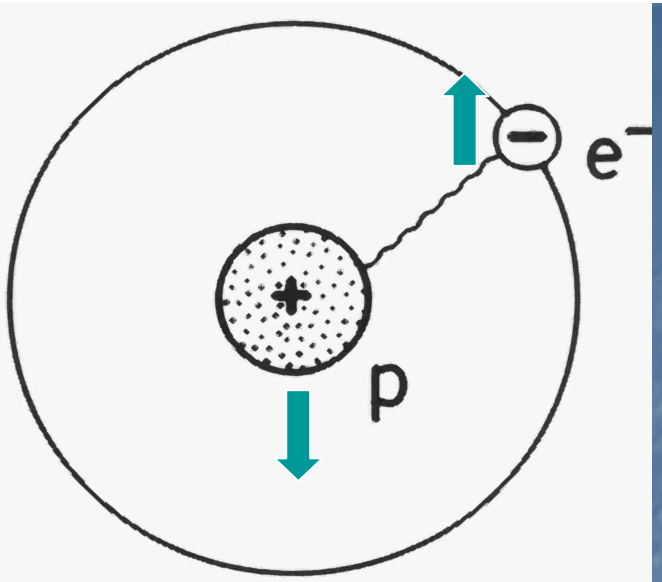
$$3,9 \bullet 10^{-14}$$

If only the scale of unification changes, the sign changes:

$$d\Lambda/dt : \Lambda \approx -31\_d\alpha/dt : \alpha$$



Wasserstoff



Wasserstoff

Hydrogen

Hydrogen

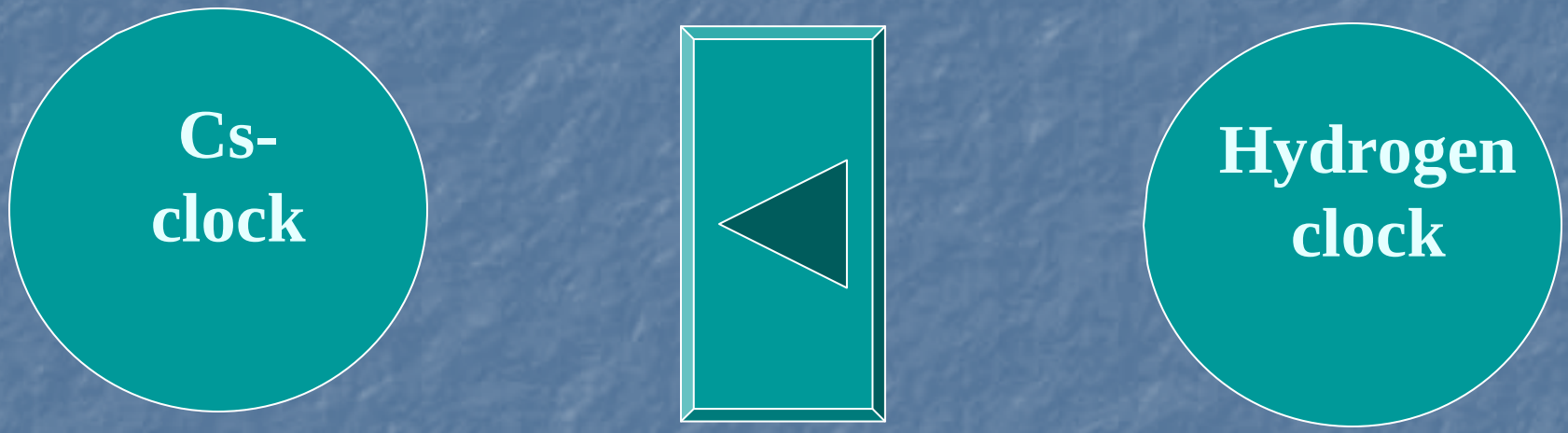
Hyperfine Interaction

21 cm line in astrophysics should change in time

NASA exp.

- Time: measured by Cesium clocks
- Hyperfine transition, involving the magnetic moment of the cesium nucleus.
- Would be affected by time change of QCD scale

Comparison



Difference: 3 CS oscillations per day

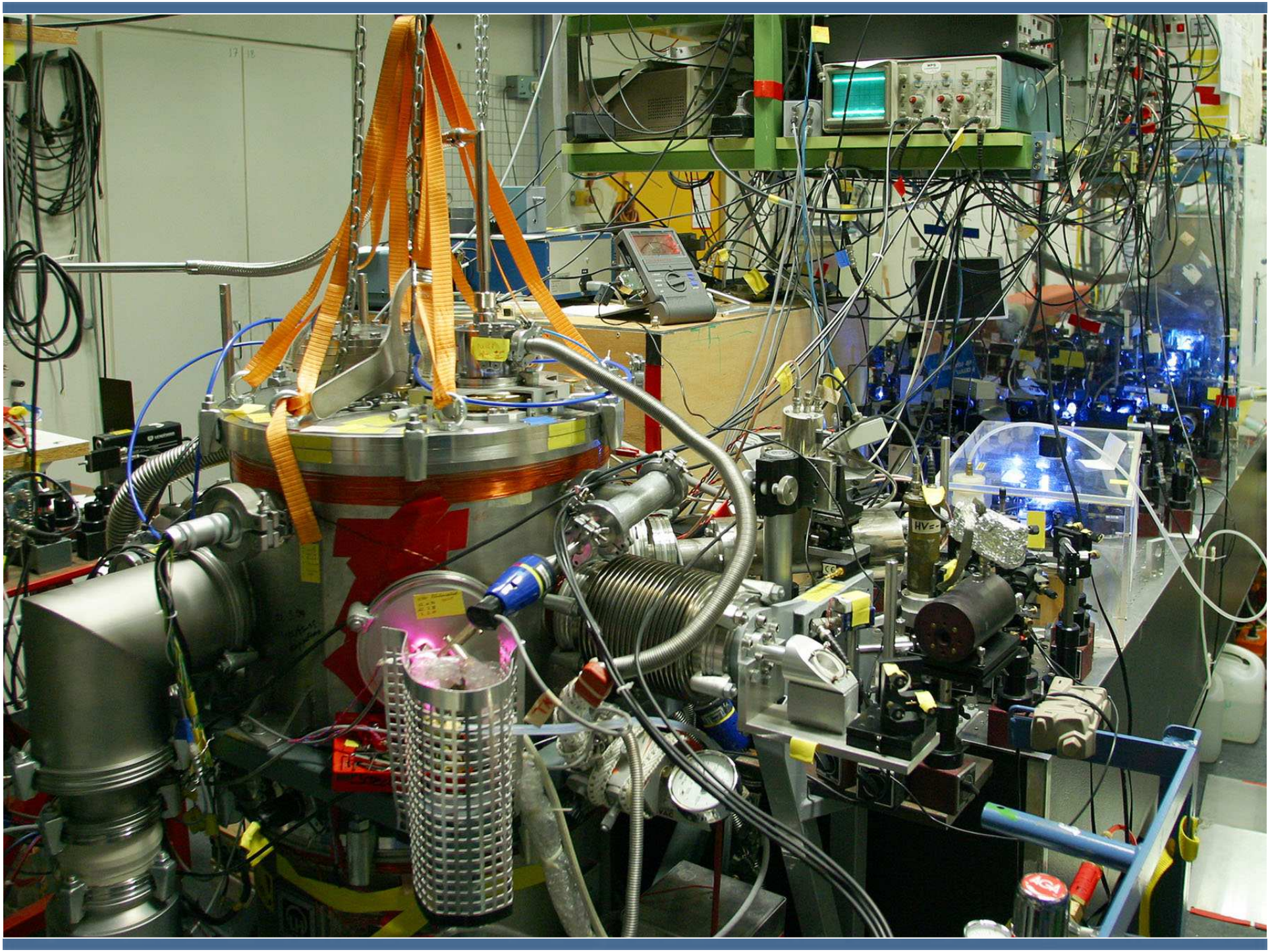
Experiment at MPQ Munich

MPQ-Experiment

486 nm dye laser in hydrogen spectrometer

Reference: cesium clock Pharao LPTF Paris

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



Measurements on Hg and Yb

$$d\mu/dt : \mu = (2.4 \pm 6.8) \bullet 10^{-15}\, yr^{-1}$$

Expected in simple model:
about 10 times more

$$d\mu/dt : \mu = 2 \bullet 10^{-14}$$

Simultaneous change of unif. coupling and unif. scale
Partial Cancellation of effect?
(expected in superstring models)

$$\frac{8}{3} d\alpha_s : \alpha_s^2 = d\alpha / dt : \alpha^2 + \frac{1}{2\pi}(const.) \_ d\Lambda_{Gut} / dt : \Lambda_{Gut}$$

Indication for effect in the new exp. at MPQ

$$d\Lambda / dt : \Lambda \approx 3 \bullet 10^{-15} / year$$

Very recently:

Reinhold et al. PRL 96 (2006)

2 quasars, 12 bn. years away

Looking for time variation of ratio proton mass / electron mass

One finds:

$$\Delta\mu / \mu \approx (2 \pm 0.6) \bullet 10^{-5}$$

$$\Rightarrow \Delta\Lambda / \Lambda \approx 3 \bullet 10^{-15} / year$$

$$(same\_sign)$$

Hänsch finds the same effect!

Proton mass time dependent

(energy not strictly conserved)

General Relativity: no strict energy conservation

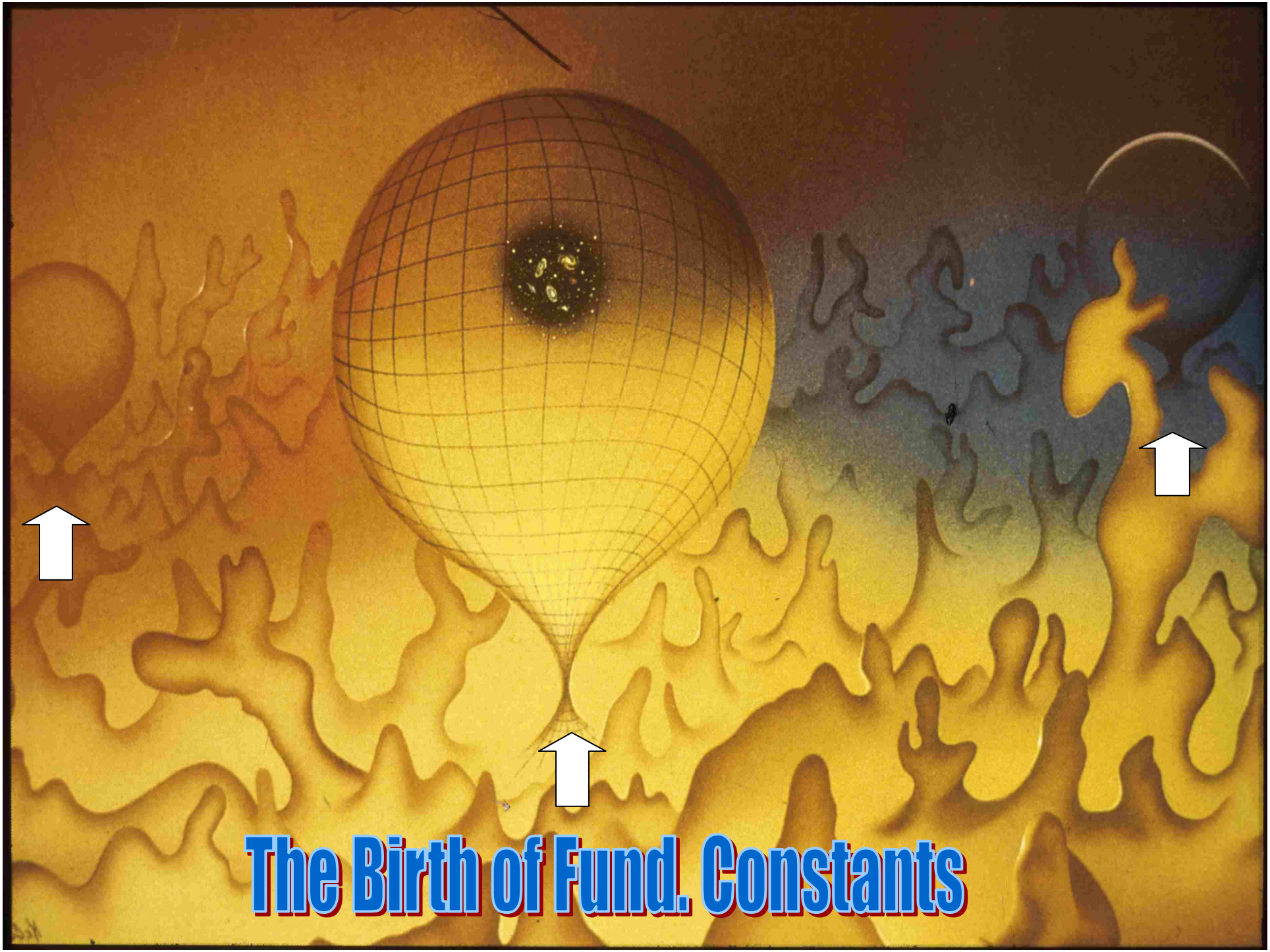
Summary

28 constants of nature, 24 of them mass parameters

Grand unification relates elm., strong and weak interactions.

Time variation of alpha leads to time variation of the QCD scale and of the weak interactions

MPQ Experiment rules out simplest model, but effect seems to be there, about a factor 10 less than naively expected, consistent mit observed variation of electron-proton-massratio.


The Birth of Fund. Constants