Fundamental Constants at High Energy and their Time Variation

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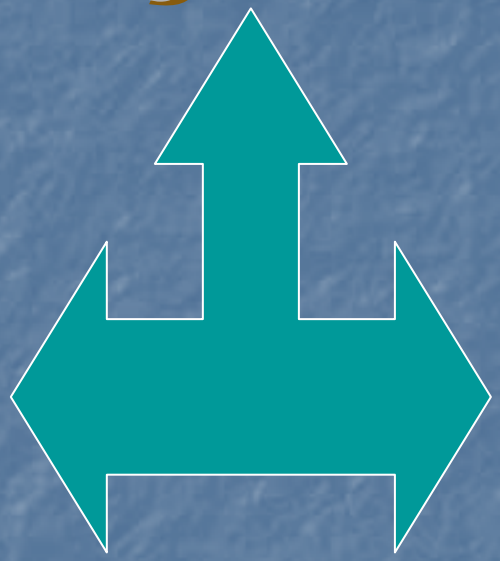
Physics



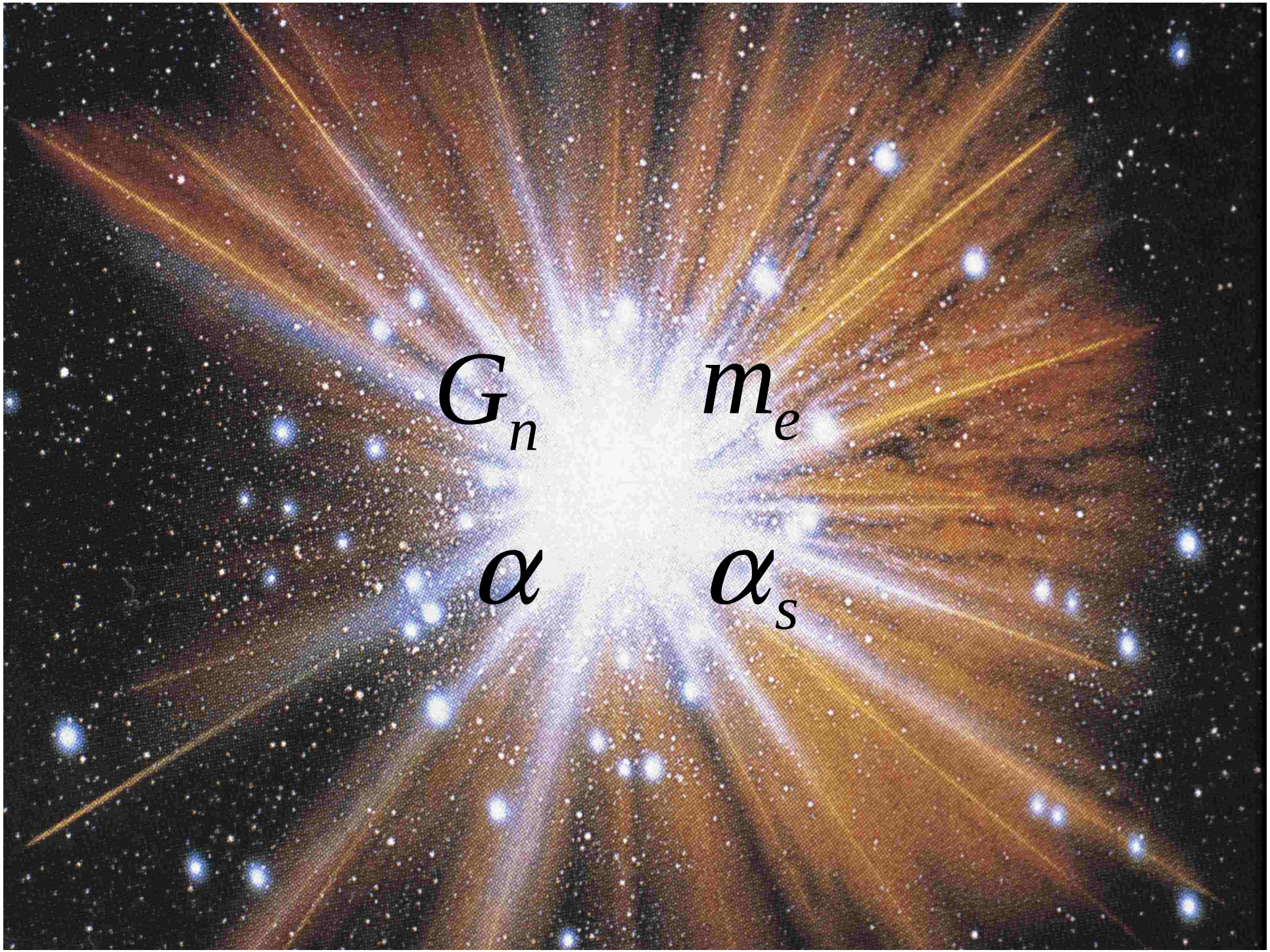
Boundary Conditions

Local Laws of Nature

Fundamental Constants - connection?

What are fundamental constants?

Cosmic Accidents?
Determined by Dynamics?
Changing in Time?


G_n
m_e
α
α_s

Example

Finestructure Constant

Sommerfeld, 1916.....

$$\alpha = e^2 2\pi / hc$$

$$1/\alpha = 137$$

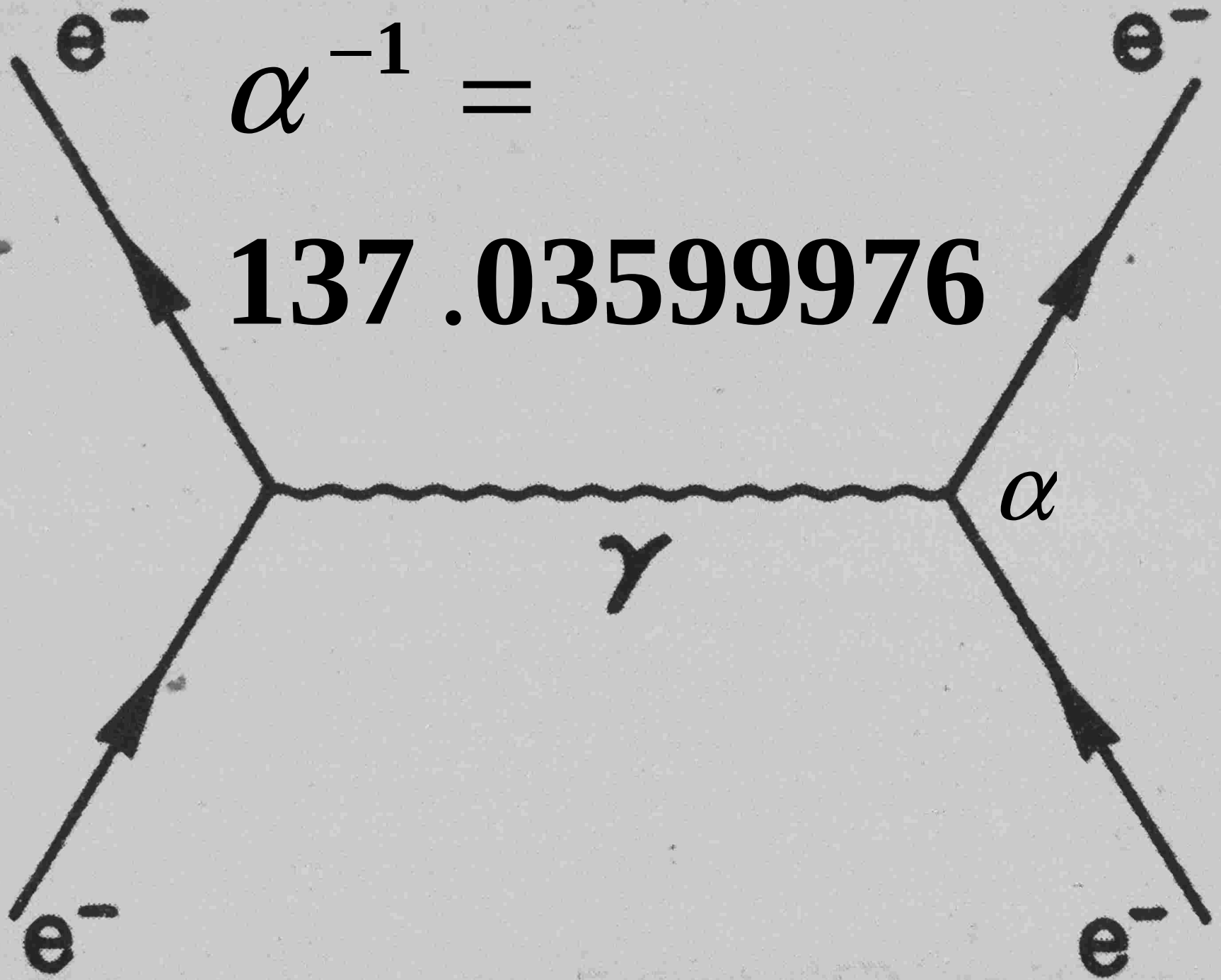
Pauli (1958): Nr 137, Zürich.....

L. Lederman, 137 Eola Road

Feynman: 137–how little we know

$$\alpha^{-1} =$$

137 .03599976



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)

QED: 2 free constants

$\alpha \qquad m_e$

(the electron mass is arbitrary ==>only one parameter)

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

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

L. Landau,

M. Gell-Mann,

F. Low

Include:
Myons, Tauons, Quarks

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

$$\alpha(200GeV)$$

LEP: $\sim 1/127$

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

agrees with theory

Oklo Phenomen

About 1.8 billion years ago, in Gabon, Westafrika.

Natural Reactor, which operated about 100 million years.

High concentration of uranium

3.7% U 235 at that time (today 0.72 %)

Moderator: water from river Oklo

The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.

Discovered in the 1970ties by french nuclear physicists

It was found:
Uranium 235 less that the normal rate
Normally: 0.720 %
==➔further investigation

➔Natural reactor

Shlyakhter, Dyson and Damour (1996)

Neutron Capture

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

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
=> constraint on elm. interaction:

alpha(Oklo)-alpha(now)/alpha

<1/10 000 000

Dyson, Damour

Change of alpha per year must be less than 1/100 000 000 000 000 000 000 per year (if no other parameters change) ==>constraint questionable

$$\delta E \approx 10^6 eV\left(\frac{\delta\alpha}{\alpha} - 10\frac{\delta X_q}{X_q} + 100\frac{\delta X_s}{X_s}\right)$$

$$X_q = {m_q}/{\Lambda}$$

$$X_s = {m_s}/{\Lambda}$$

(Flambaum, ... F. and Calmet)

No limit on variation of alpha

Other basic paramters:

Nucleon mass!?

=======➔QCD

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

First calculation of a mass in physics

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

Nucleon Mass in QCD:

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

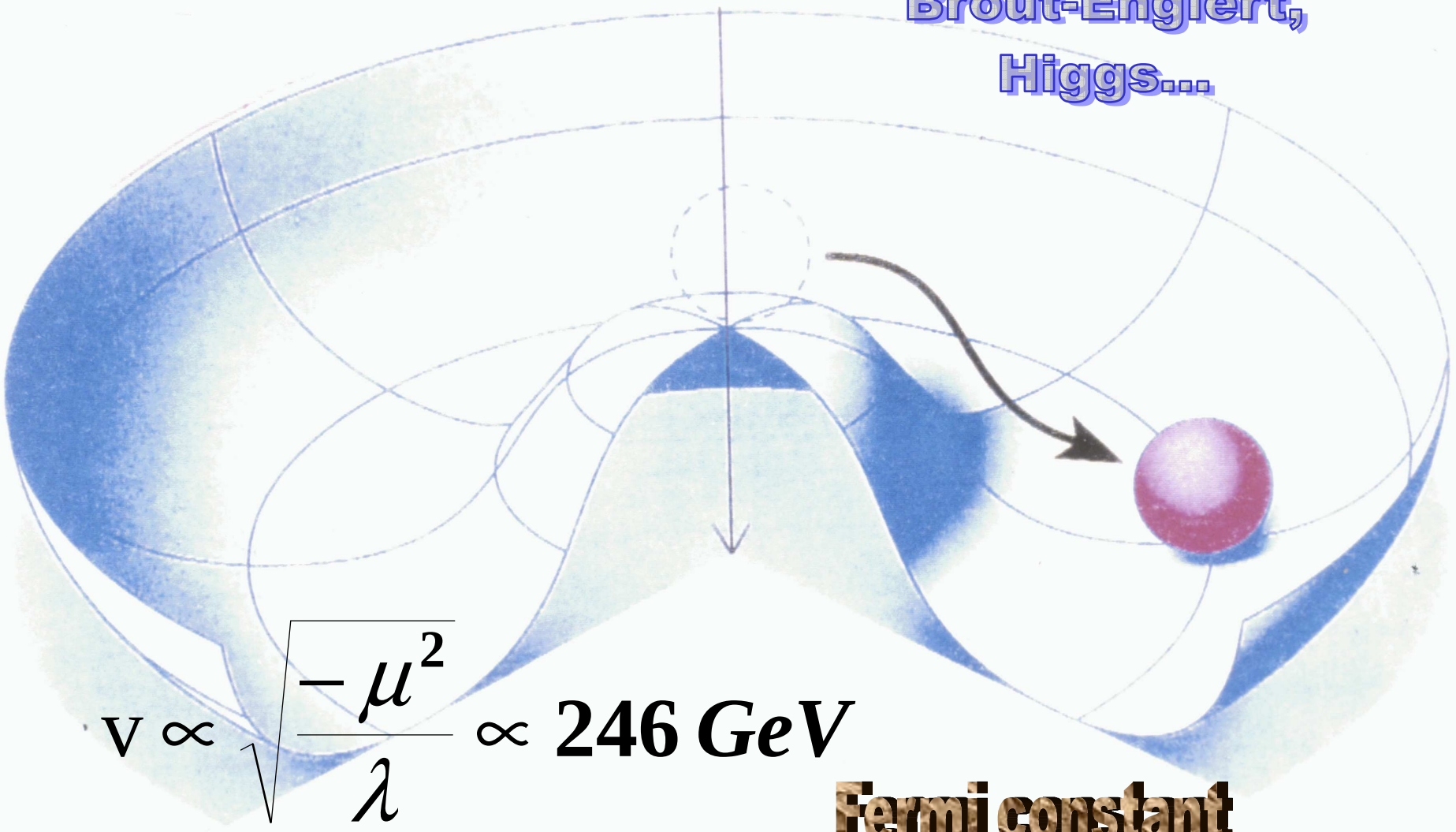
Example: **QCD** **u** **d** **s+c** **QED**

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

Masses of weak bosons?

Mass and Symmetry Breaking

Brout-Englert, Higgs...



$$v \propto \sqrt{\frac{-\mu^2}{\lambda}} \propto 246\,GeV$$

Fermi constant

Masses of W-Bosons are generated

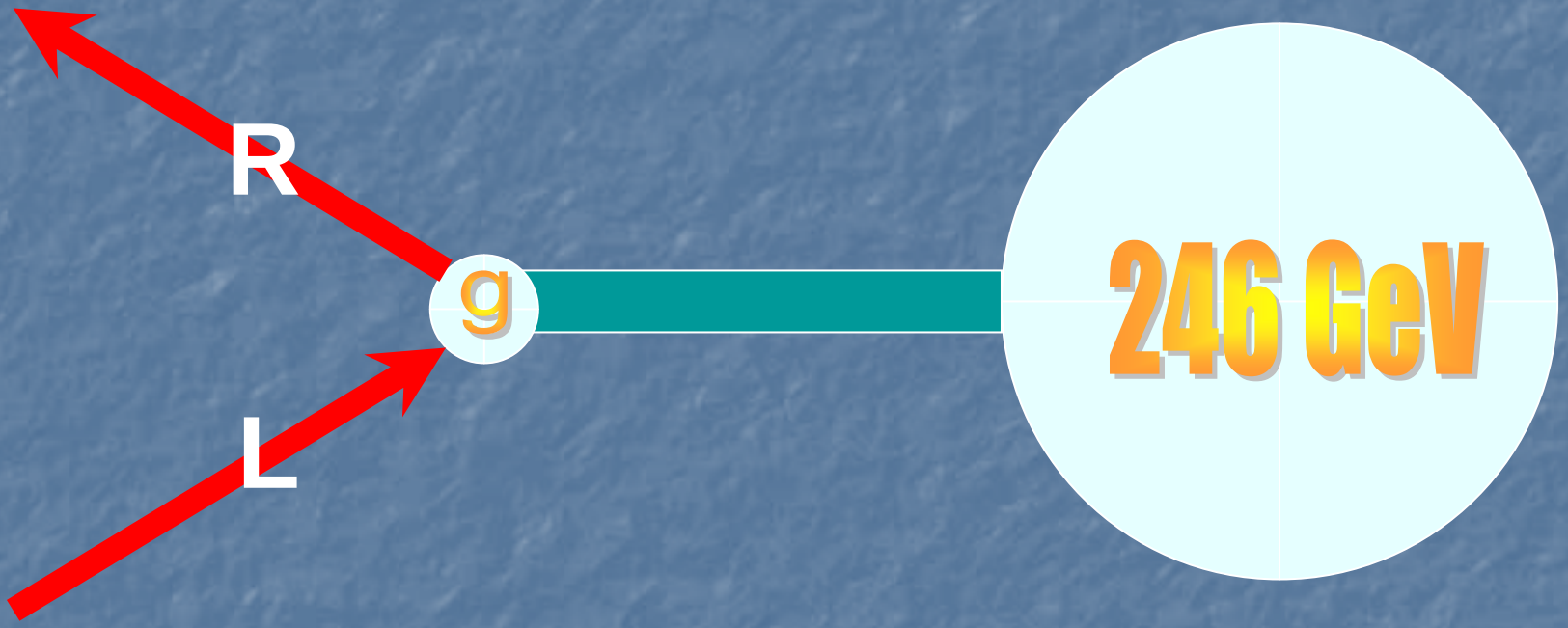
LHC: Search for Higgs particle, starting 2009

Fermion Masses???

The Dark Corner of HEP
Fermion Masses: Arbitrary

what do these masses mean?

(Higgs mech.)



$$m_e = 0.511\,MeV = 0.0000021 \bullet 246\,GeV = 2.00 \bullet 10^{-30}\,lb$$

Sam Nunn

6 Constants for stable matter

QED

α

m_e

m_u

m_d

QCD

Λ

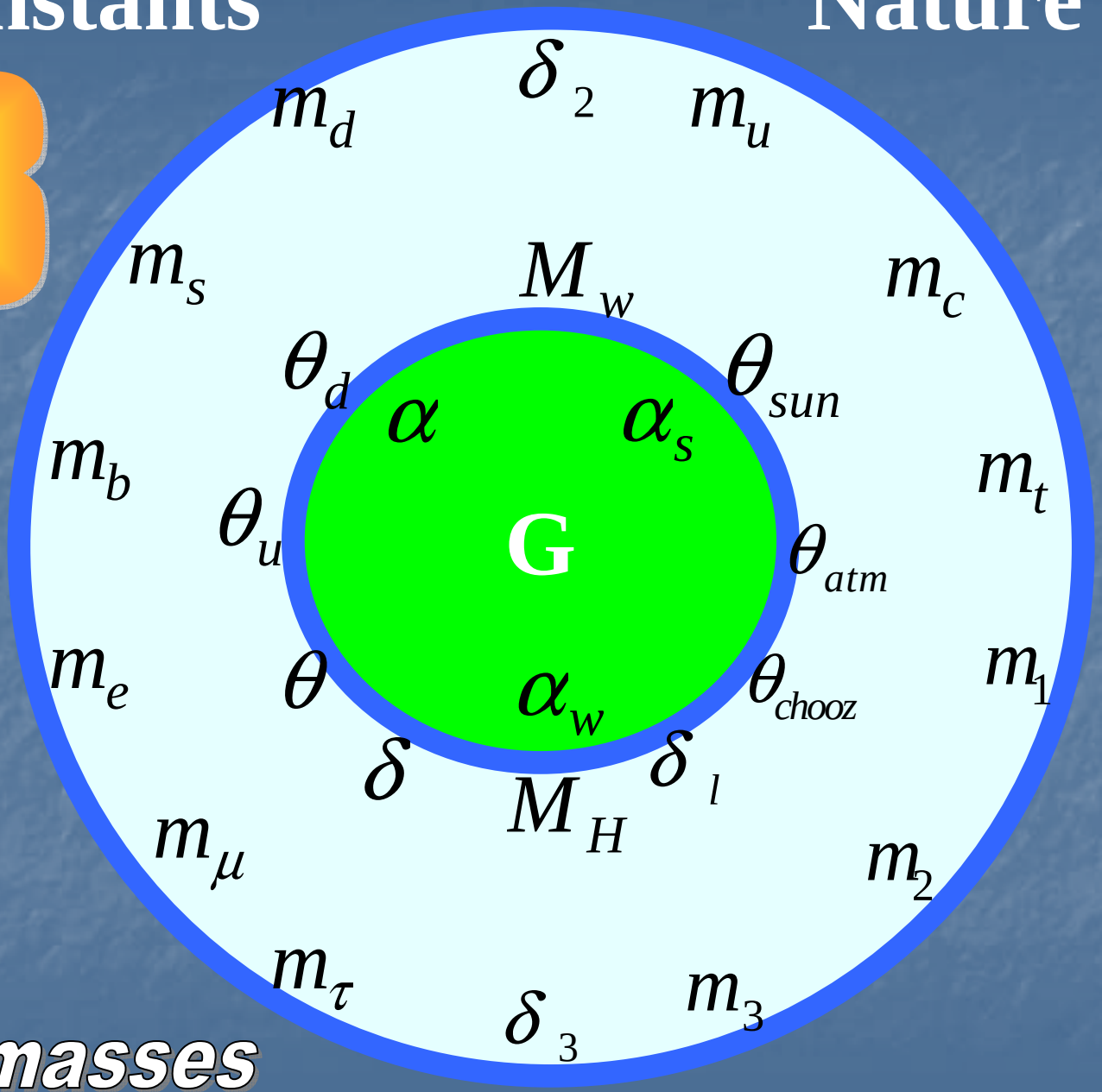
➔ Atoms, Nuclei

Particle Physics:

many more fundamental constants

Constants of Nature

28



24 are masses

Relations between the various constants?

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) ?!

1 / 207 1 / 207

Quark Masses:

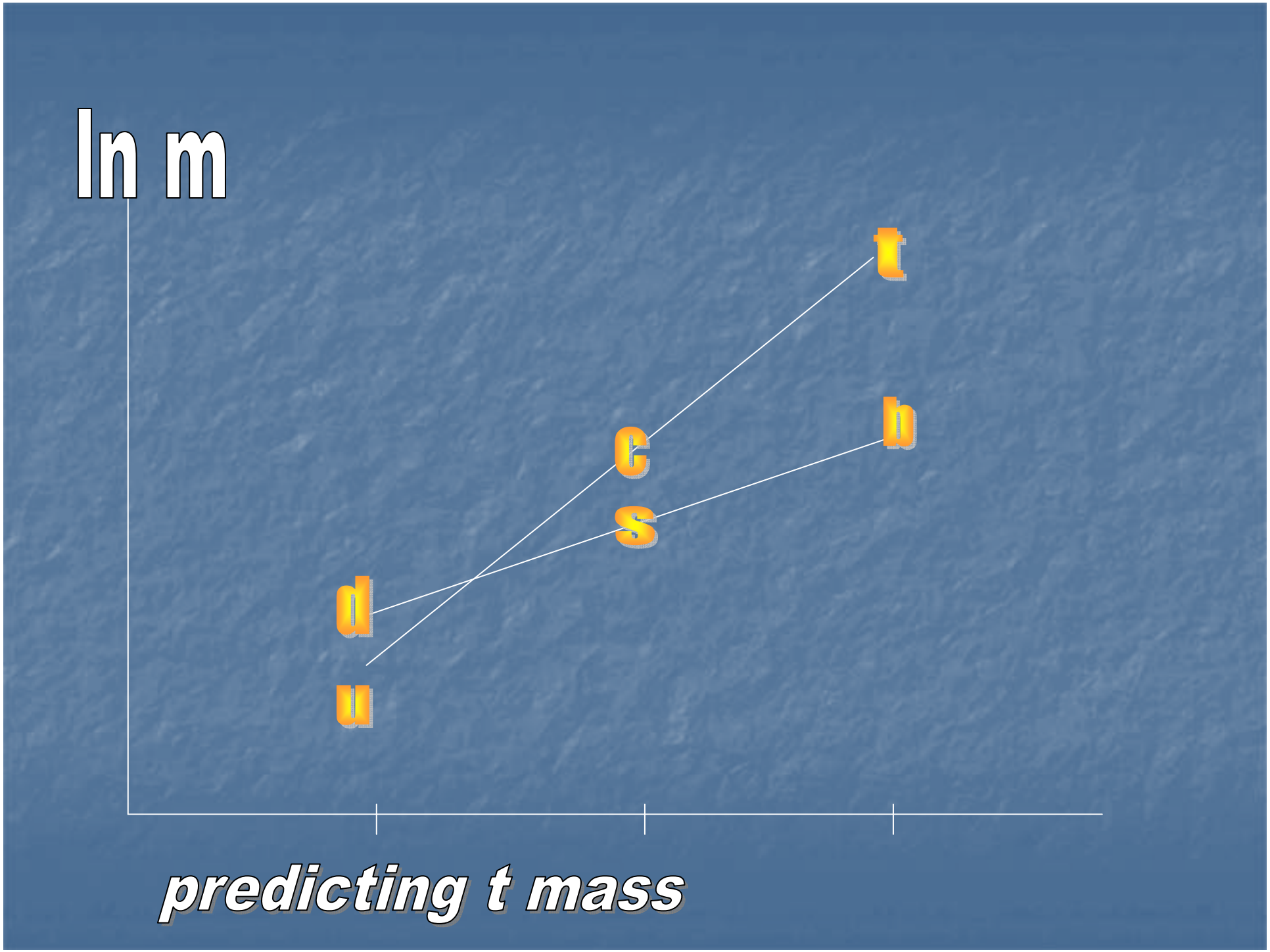
- Observed:

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

$$1/207 \qquad\qquad 1/207$$

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

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


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

Mass matrix:

discrete symmetry

$$M = \begin{bmatrix} 0 & A & 0 \\ A^* & C & B \\ 0 & B^* & D \end{bmatrix}$$

texture zero

F., Xing

(works extremely well)

Higgs‟ v.e.v.

v = 246 GeV

(Fermi constant)

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

accident or due to a symmetry?

Relations of this type allow to reduce the number of fundamental constants to about 19

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, Wolf, Flambaum...)

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

Quasars, back to 11 bn years in time

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

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

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

Time variation of fundamental constants expected in superstring theories
(extra dimensions – change in time)

Grand Unification

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

(Glashow, Georgi: 1974)

Now excluded by experiment.

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

(Fritzsch - Minkowski, Georgi : 1975)

Grand Unification

3 coupling constants

elm., weak and strong int.

reduced to two parameters:

unif. scale and unified coupling

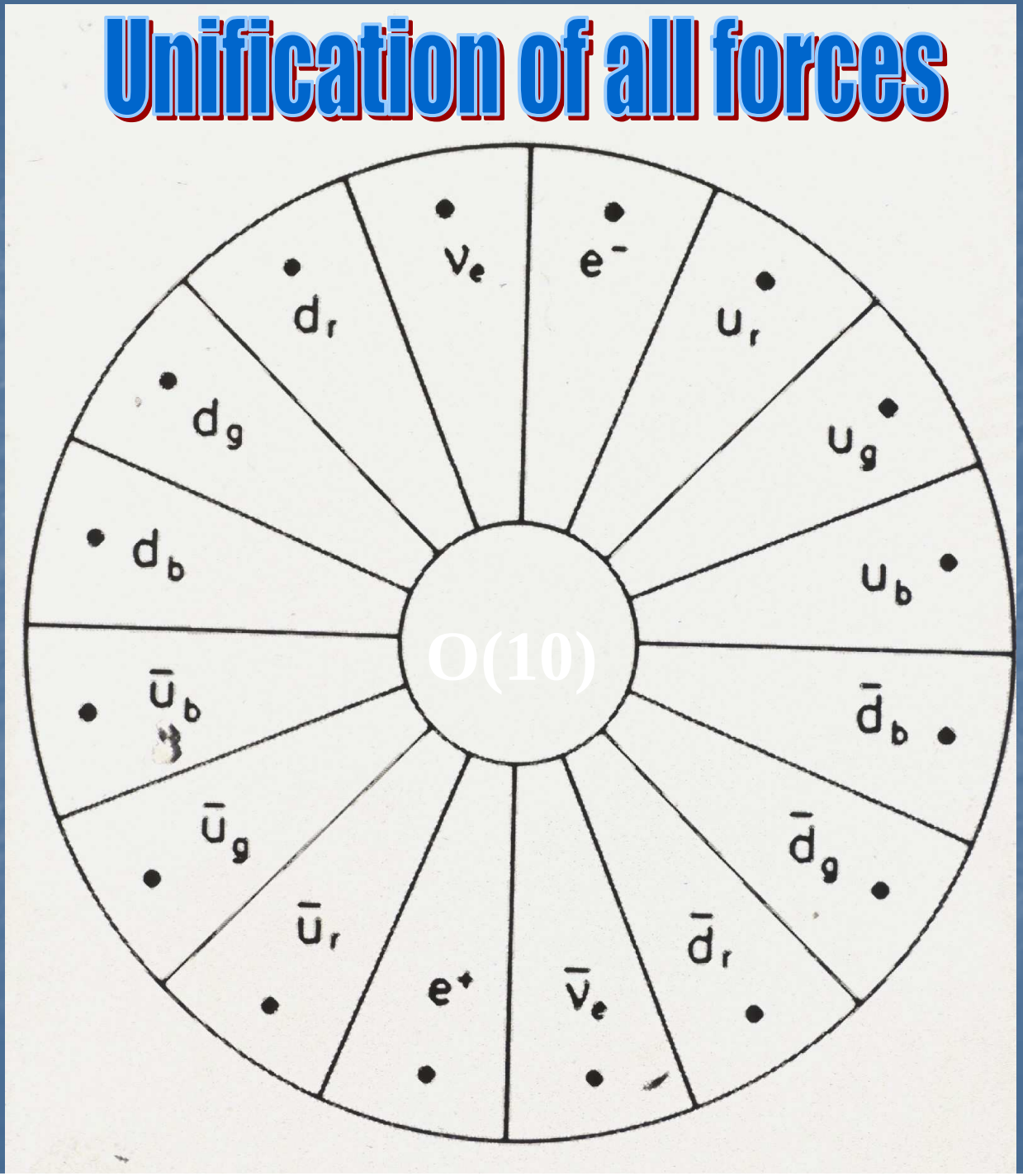
(one constant less)

Fermions in 16-plet

(incl. righthanded neutrinos)

Unification of all forces

Neutrinos are massive



In SO(10):

lefthanded and righthanded neutrinos

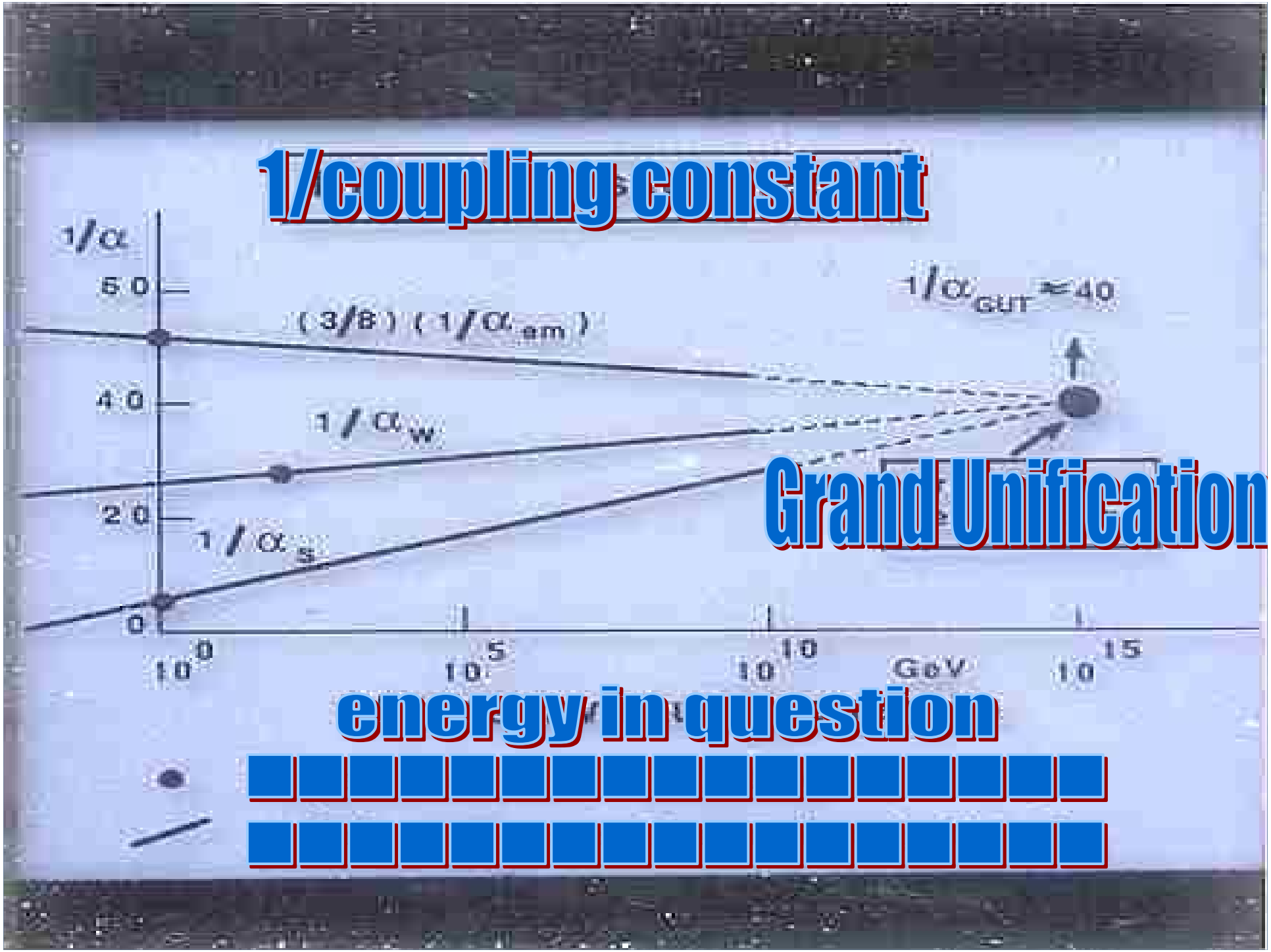
Electroweak theory:

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

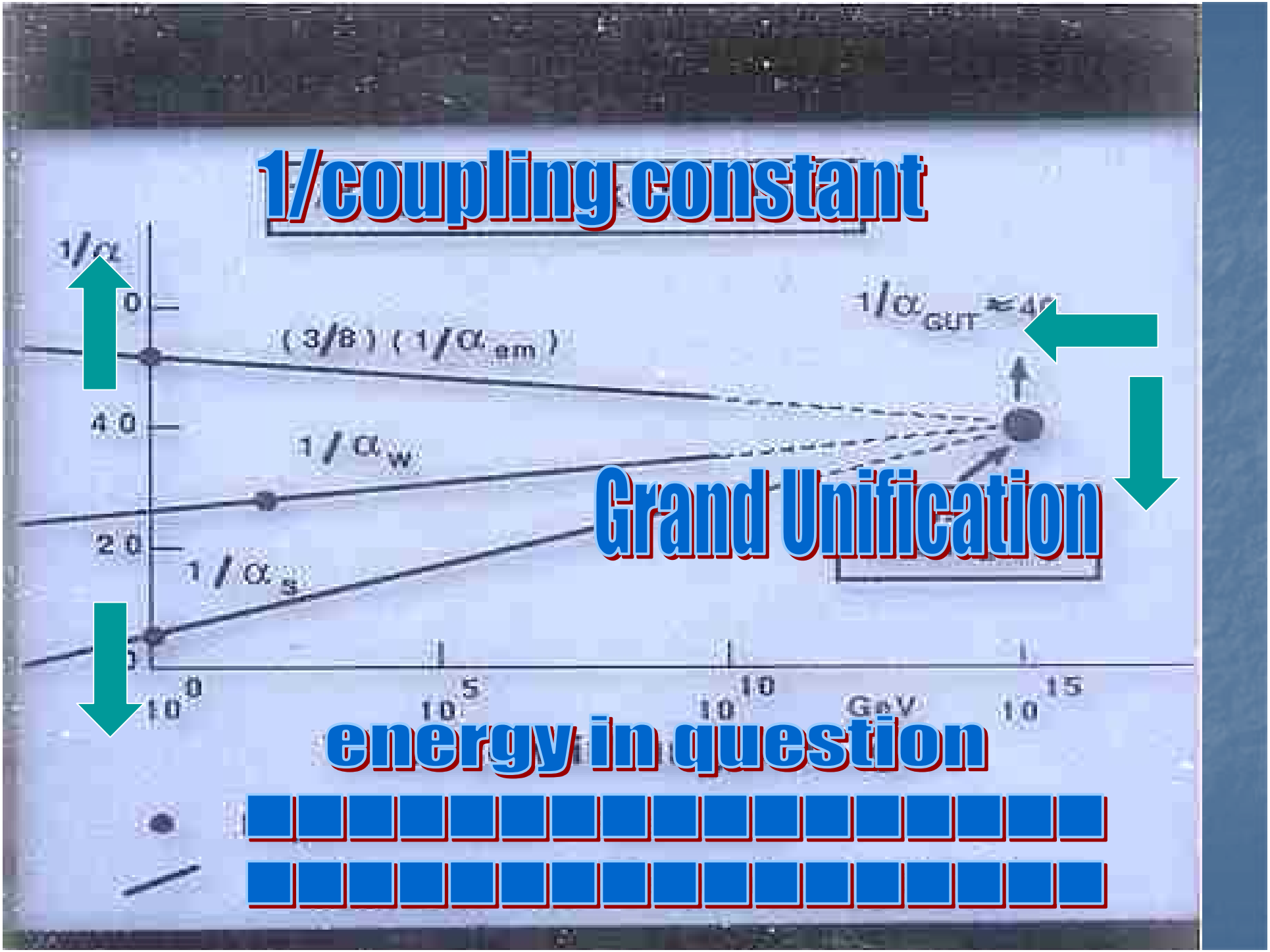
U(1): (B-L)

New energy scale for righthanded SU(2)

(related to neutrino masses?)


1/coupling constant
1/α
50
40
20
0
(3/8)(1/α em)
1/α GUT ≈40
1/α W
1/α S
10 0
10 5
10 10
GeV
10 15
Grand Unification
energy in question

time change of alpha?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10^15
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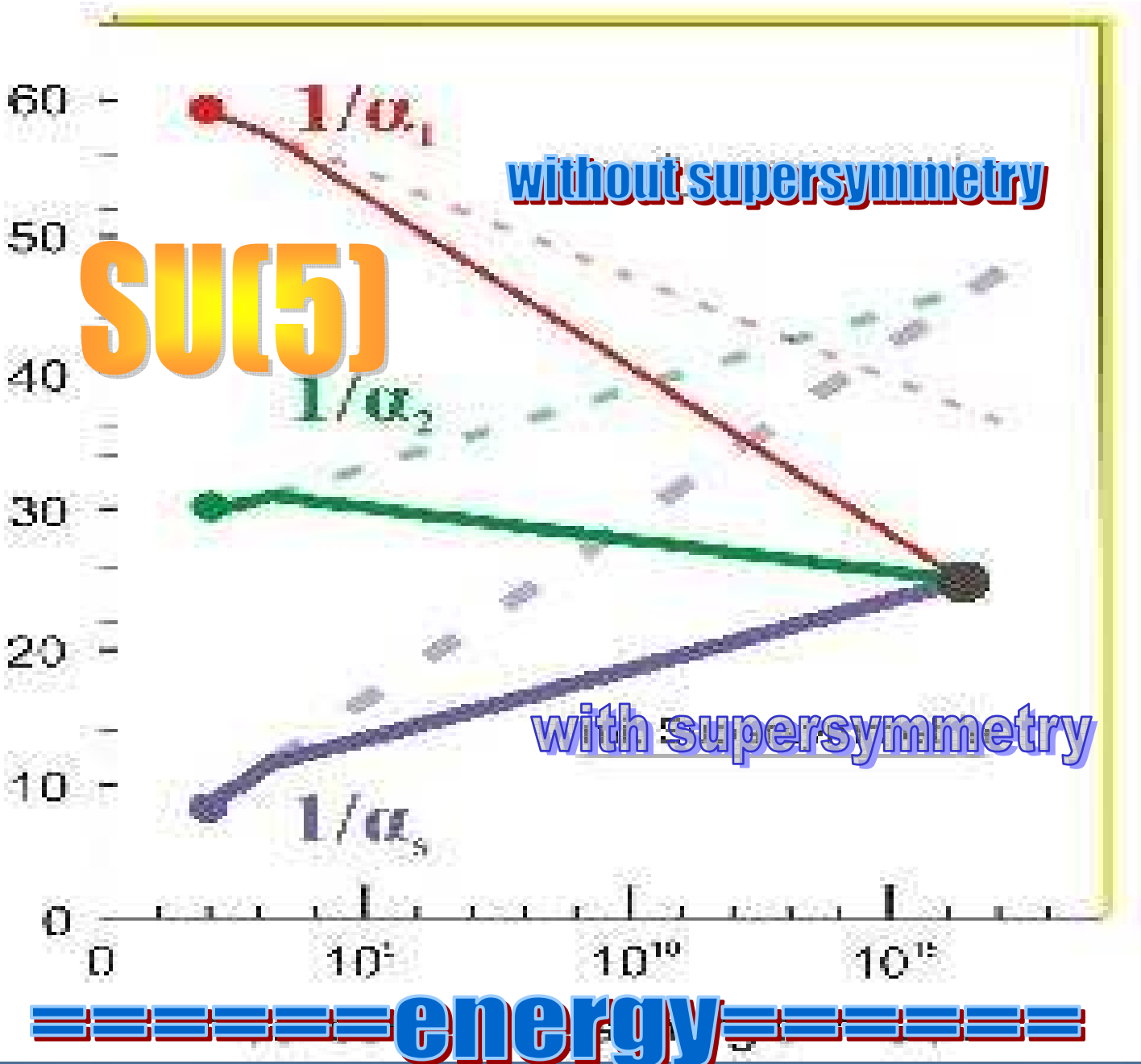

SU(5)
without supersymmetry
with supersymmetry
60
50
40
30
20
10
0
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
0
10^{5}
10^{10}
10^{15}
energy

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

Calmet, F. - Langacker, Segre (2002)

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

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

$$d\Lambda/dt : \Lambda \approx 38{,}8\_d\alpha/dt : \alpha$$

dimensionless: Λ / m_e

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:

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

Can this be tested by experiments?

Time: measured by Cesium clocks

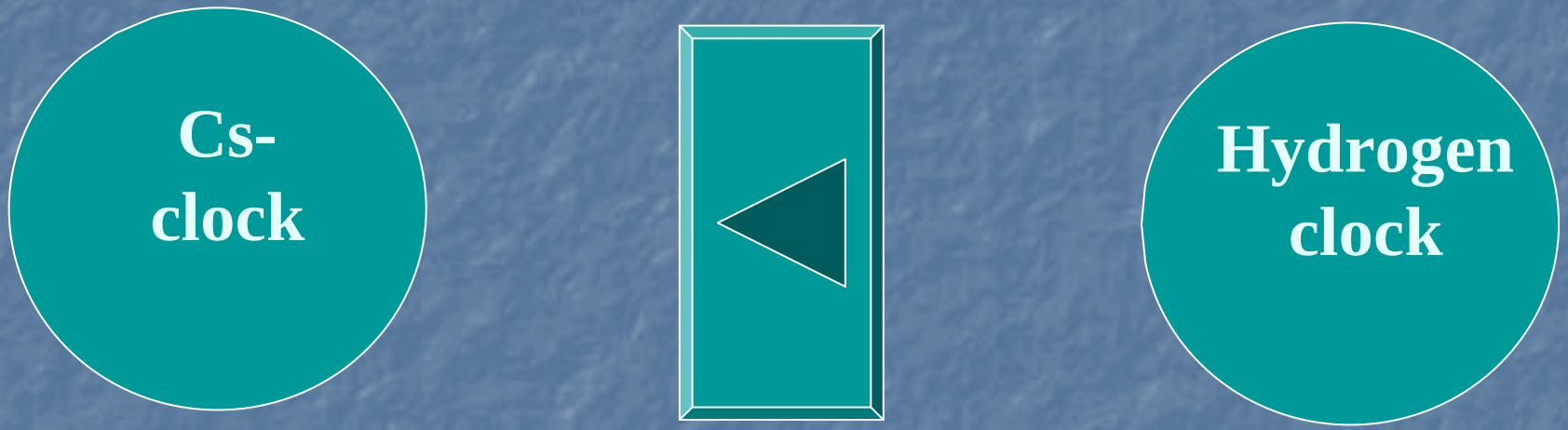
Hyperfine transition, involving the magnetic moment of the cesium nucleus.

Would be affected by time change of QCD scale

Cesium: 9 192 631 770 Hz

(definition of time)

Comparison



Difference: 3 CS oscillations per day

Experiment at MPQ Munich and NIST Boulder

(T. Hänsch, MPQ)

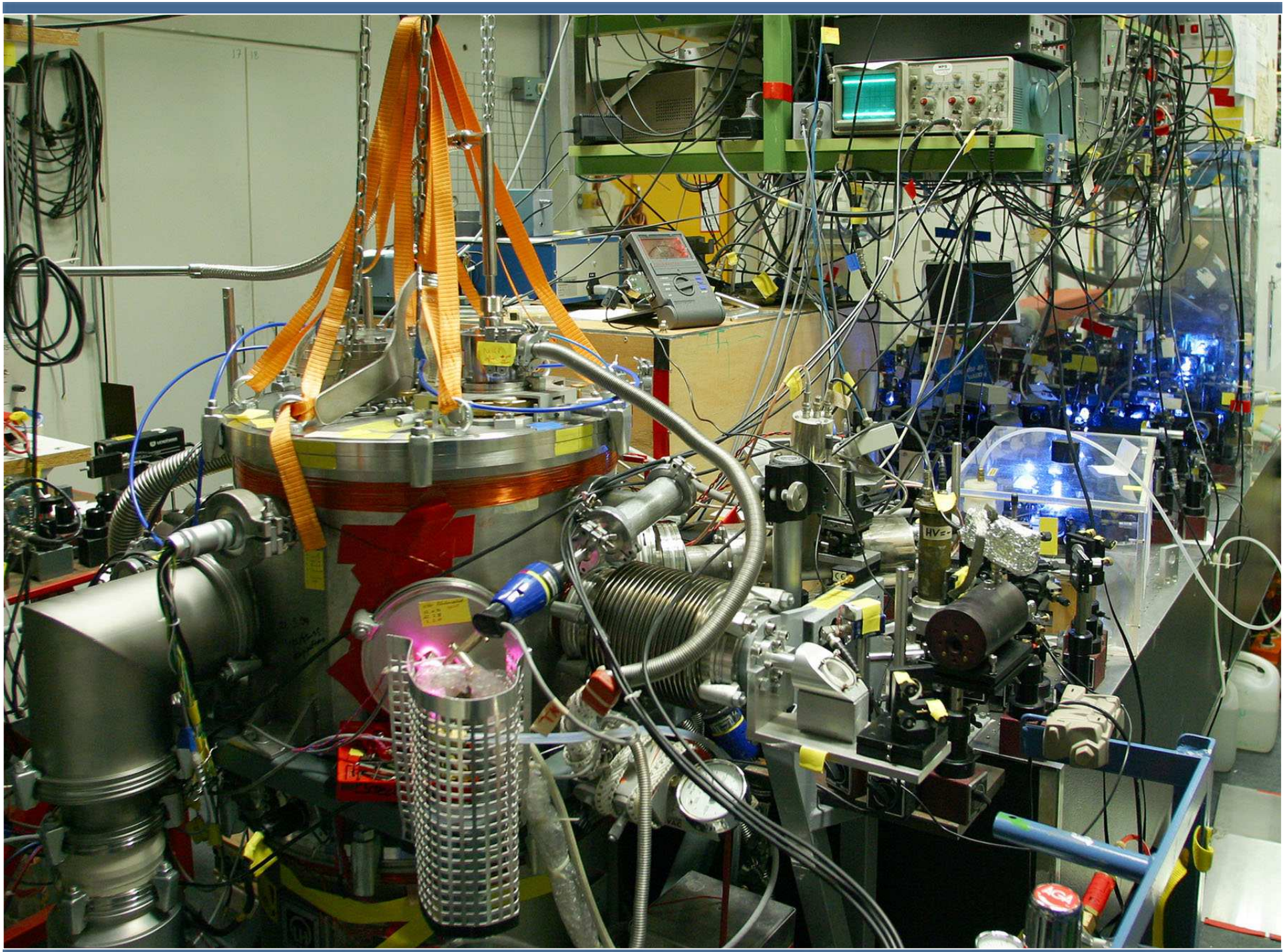
Nobel prize 2006

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



Measurement:

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

Expected in simple model:
about 10 times more

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

seems excluded!

Simultaneous change of unif. coupling and unif. scale

Partial Cancellation of effect?

(expected in superstring models)

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

Indication for effect in the new exp. at MPQ:

$$d\Lambda / dt : \Lambda \approx (3 \pm 1) \bullet 10^{-15} / year$$

(Hänsch, preliminary)

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:

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

But: New experiment by Webb et al.

No time variation of this mass ratio seen

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

Hänsch finds the same effect

(same sign)

If true:

All masses of atomic nuclei will depend on time!

Masses of nuclei depend on the age of the universe

But:

limit from molecular spetra (Flambaum, Kozlov)

$$\mu = m_e / M_p$$

$$\dot{\mu} / \mu = (1 \pm 3) \bullet 10^{-16}\, yr^{-1} = -\dot{\Lambda} / \Lambda$$

(MPQ: measurement today!)

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.

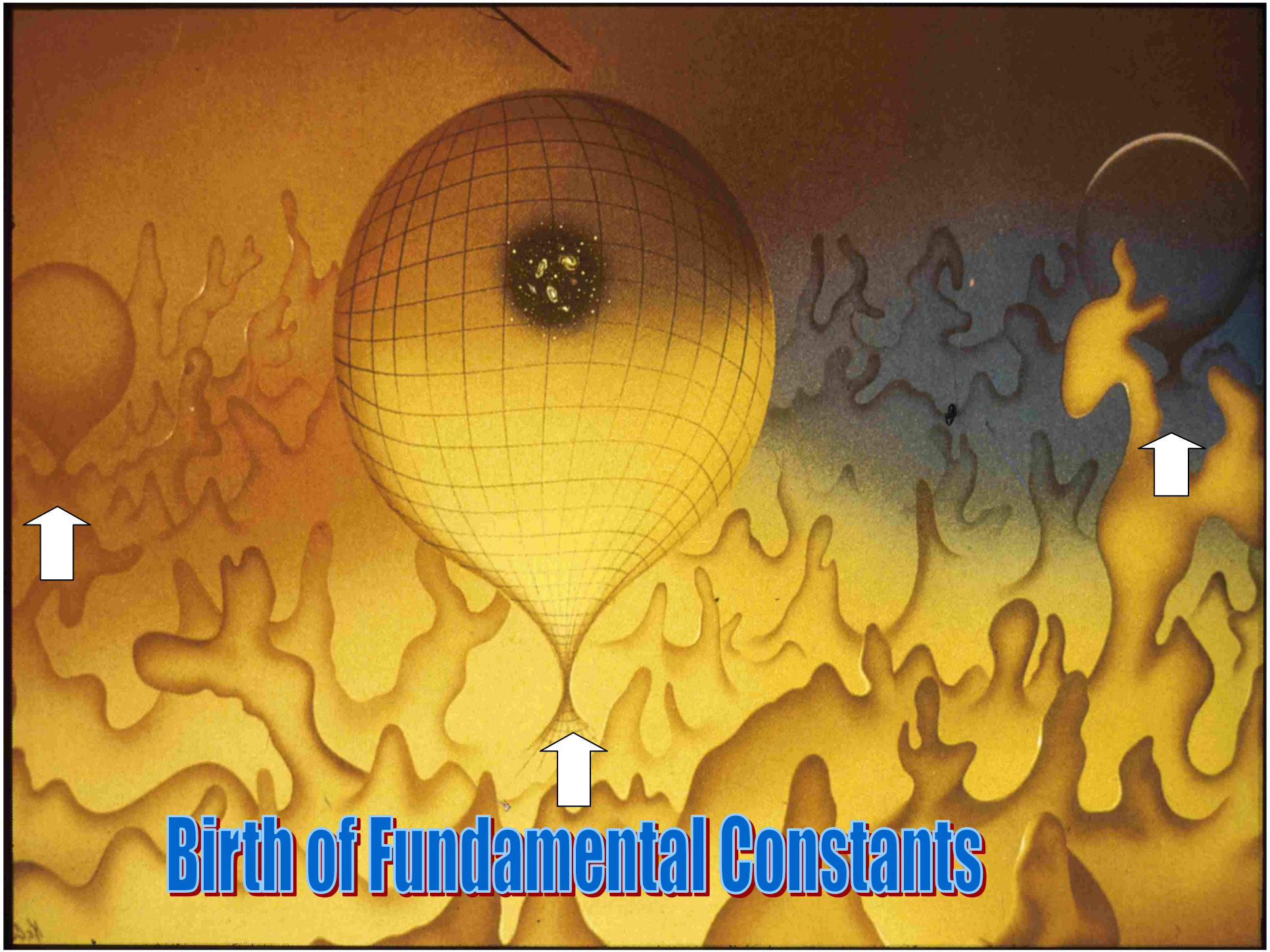
Necessary:

Both unification scale
and
unified coupling
must change in time.
(expected in superstring models)

QCD mass scale changes in time

Masses of atomic nuclei

change in time


Birth of Fundamental Constants