Fundamental Constants

and their

Time Variation

H. FRITZSCH

LMU MUNICH

fundamental constants

PARTICLES NUCLEI

ATOMS SOLIDS

STARS GALAXIES

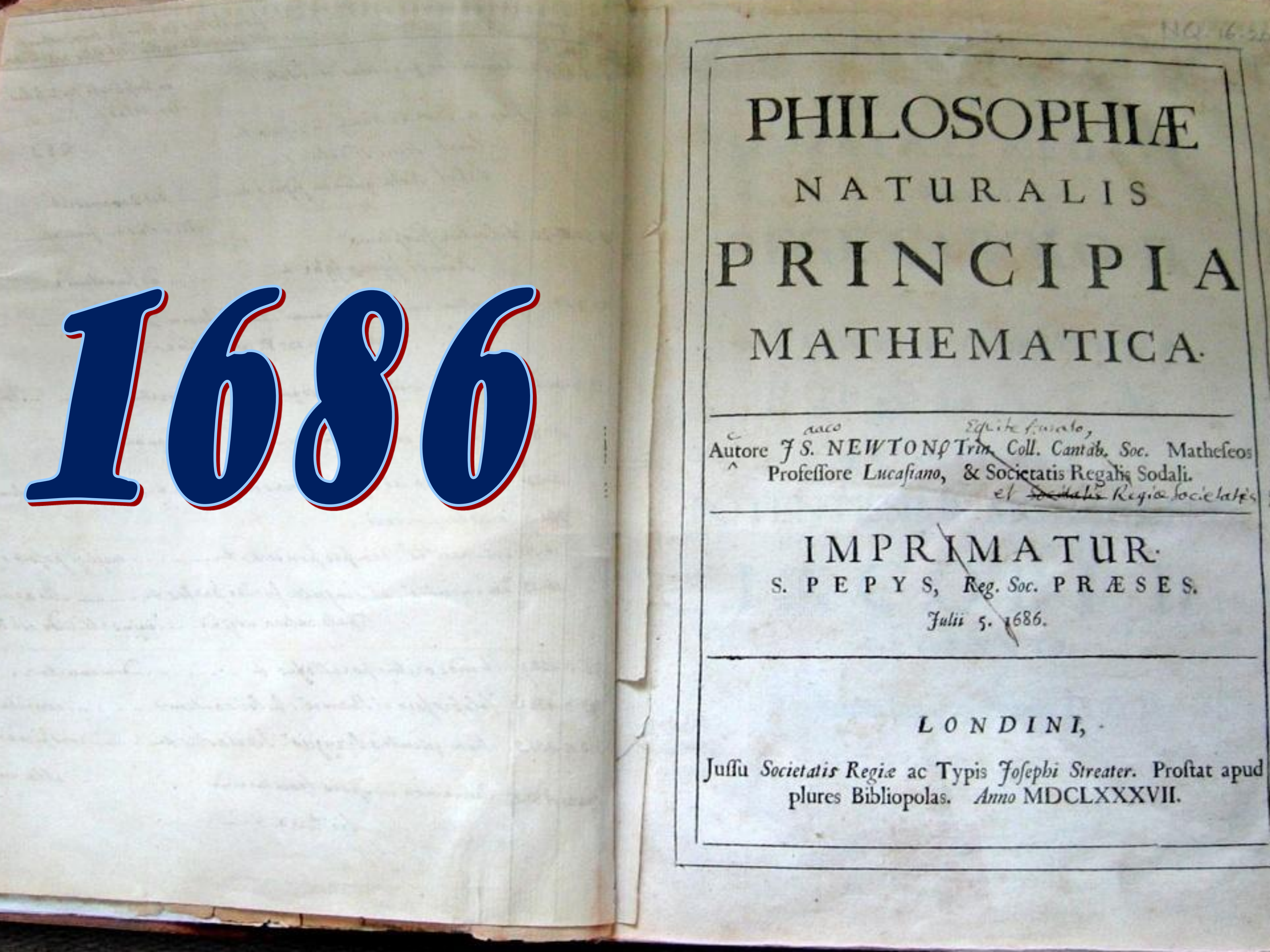
COSMOLOGY

first fundamental constant

1686

NEWTONS CONSTANT

G


1686

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S.* NEWTONO, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

GRAVITY

$$force = G \bullet \frac{m_1 \cdot m_2}{r^2}$$

$$G = 6.674 \bullet 10^{-11} \frac{m^3}{kg \cdot s^2}$$

FIRST BASIC CONSTANT

1897

J. J. Thomson

DISCOVERY OF ELECTRON

$$m(electron) \cong 0.511 \quad MeV$$

second basic constant

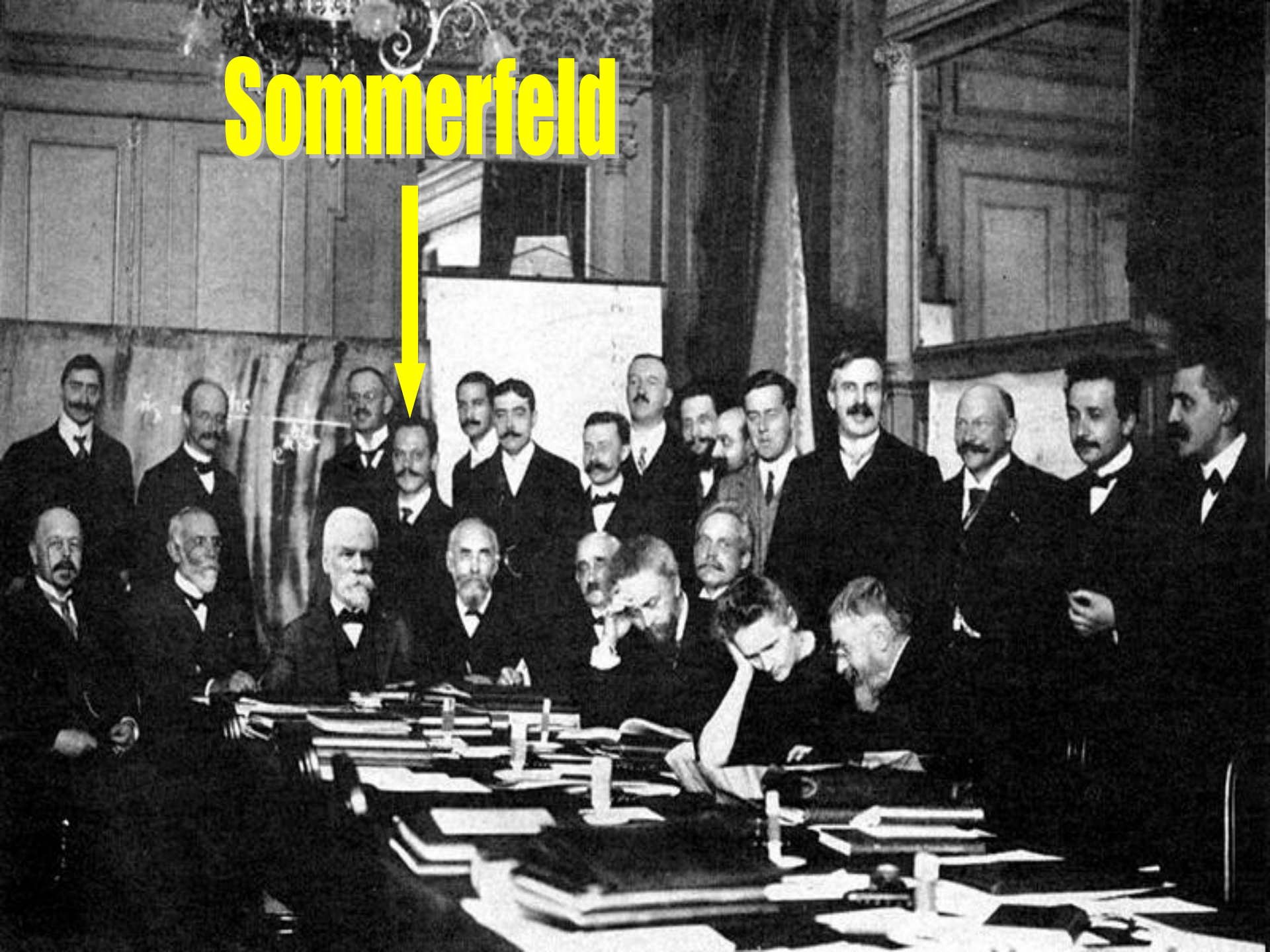
Arnold Sommerfeld, 1916

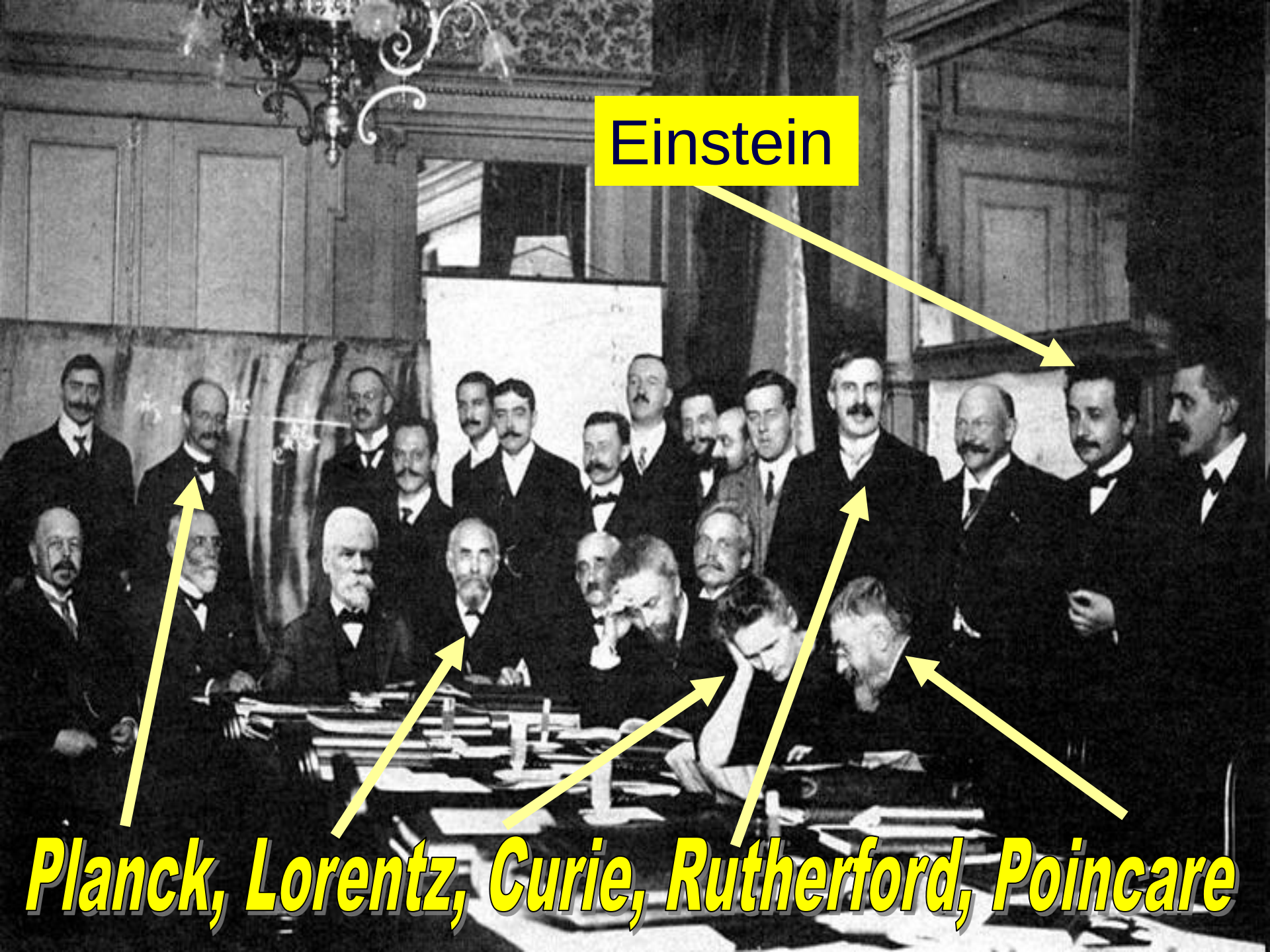
3. CONSTANT

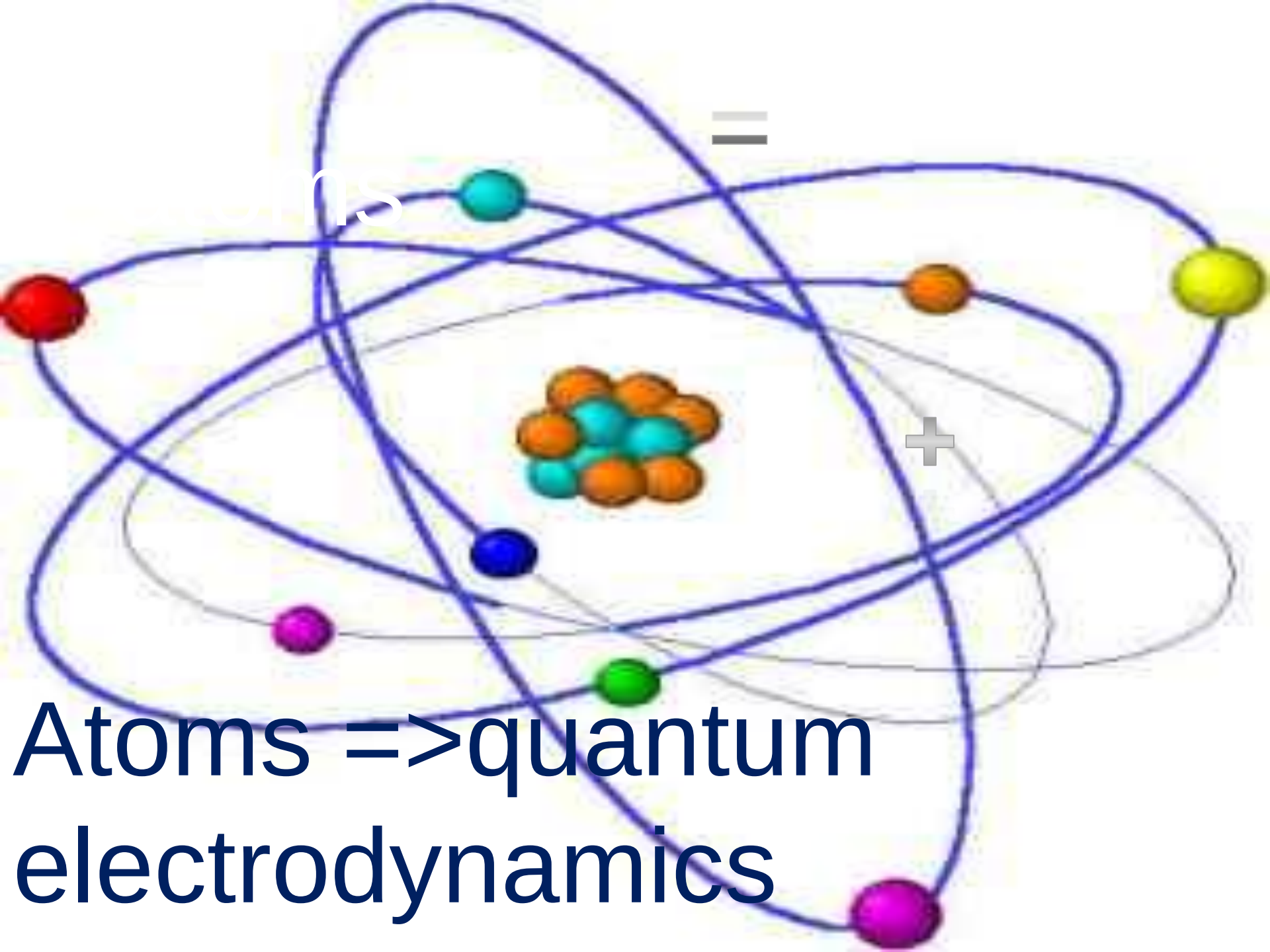
fine-structure constant

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


Solvay


Sommerfeld


Einstein
Planck, Lorentz, Curie, Rutherford, Poincare

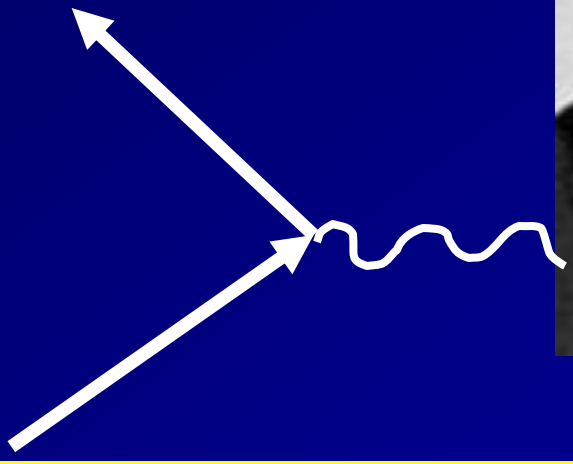


Atoms =>quantum electrodynamics

1935

W. Heisenberg

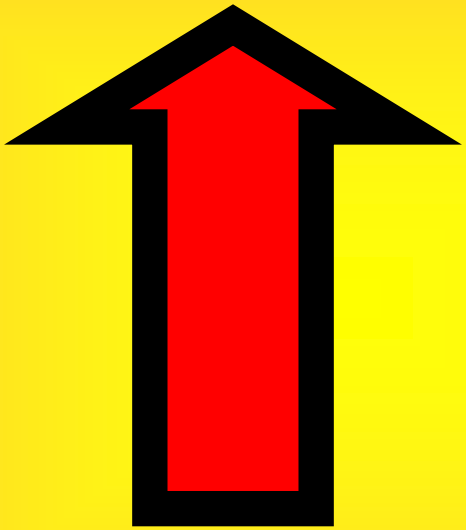
W. Pauli



$$e\overline{\Psi}\gamma_\mu\Psi A^\mu$$

minimal interaction => QED

FIRST GAUGE THEORY

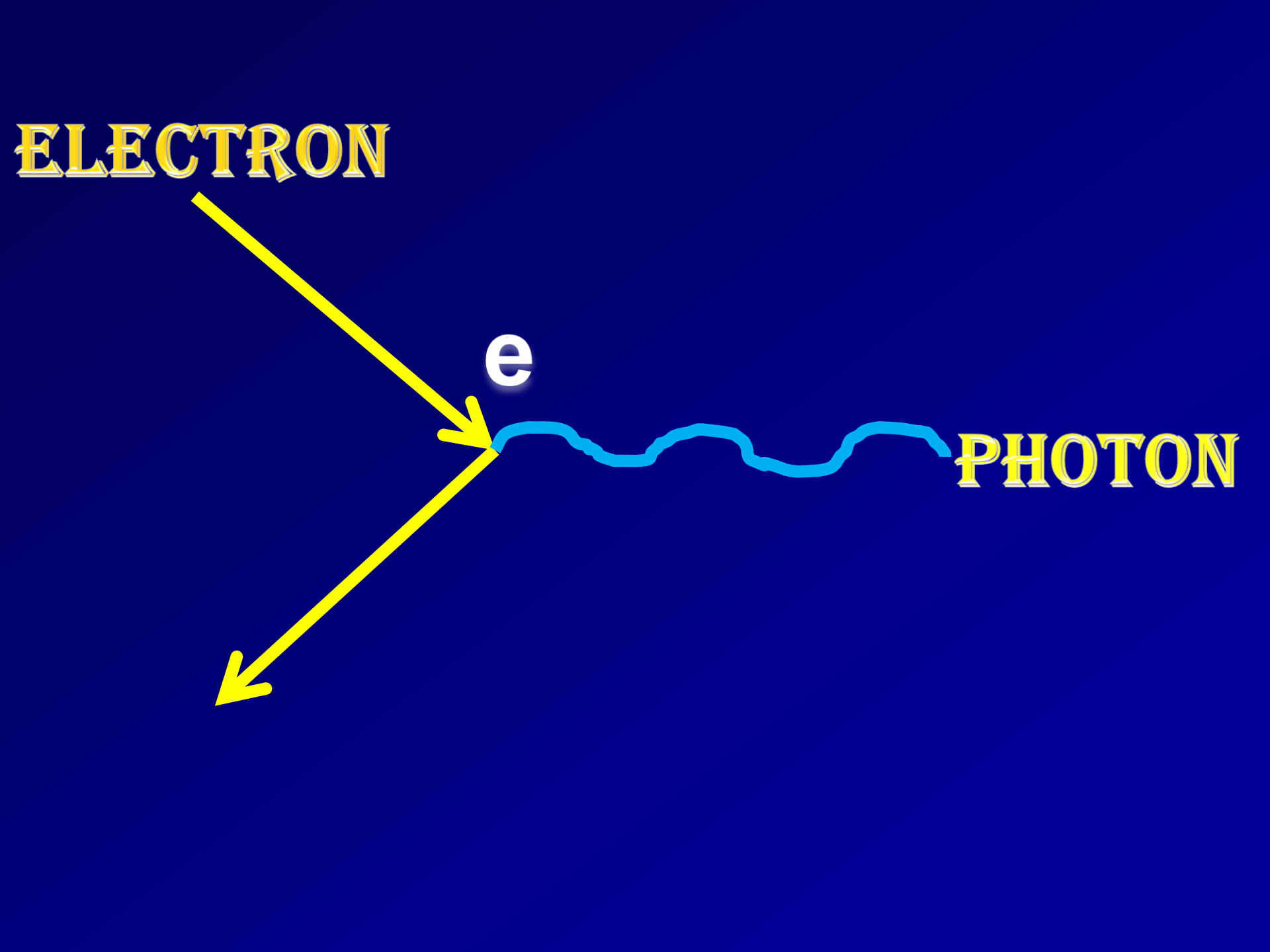


QED

QED

Gauge Group:

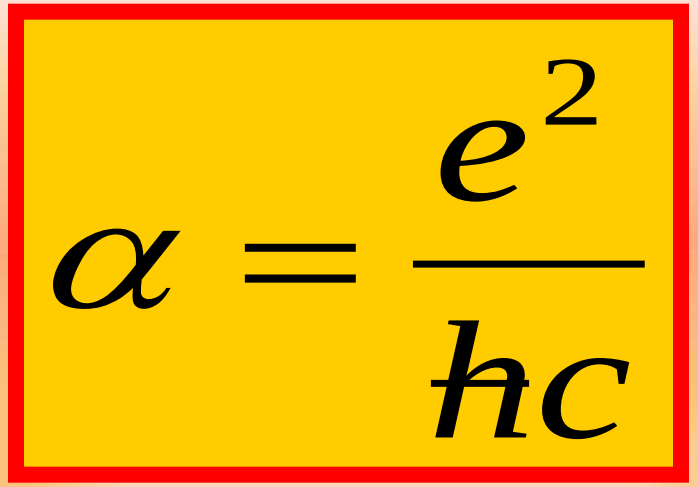
$$U(1) \Rightarrow e^{i\alpha(x)}$$


ELECTRON
e
PHOTON

fine-structure constant

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

$$\hbar, c \Rightarrow 1$$



electrodynamics

relativity

quantum theory

$1/\alpha \approx 137$

1958

PAULI

NR 137

KANTON-SPITAL

ZÜRICH

Q E D

2 FUNDAMENTAL CONSTANTS

α m_e

1964 ===>

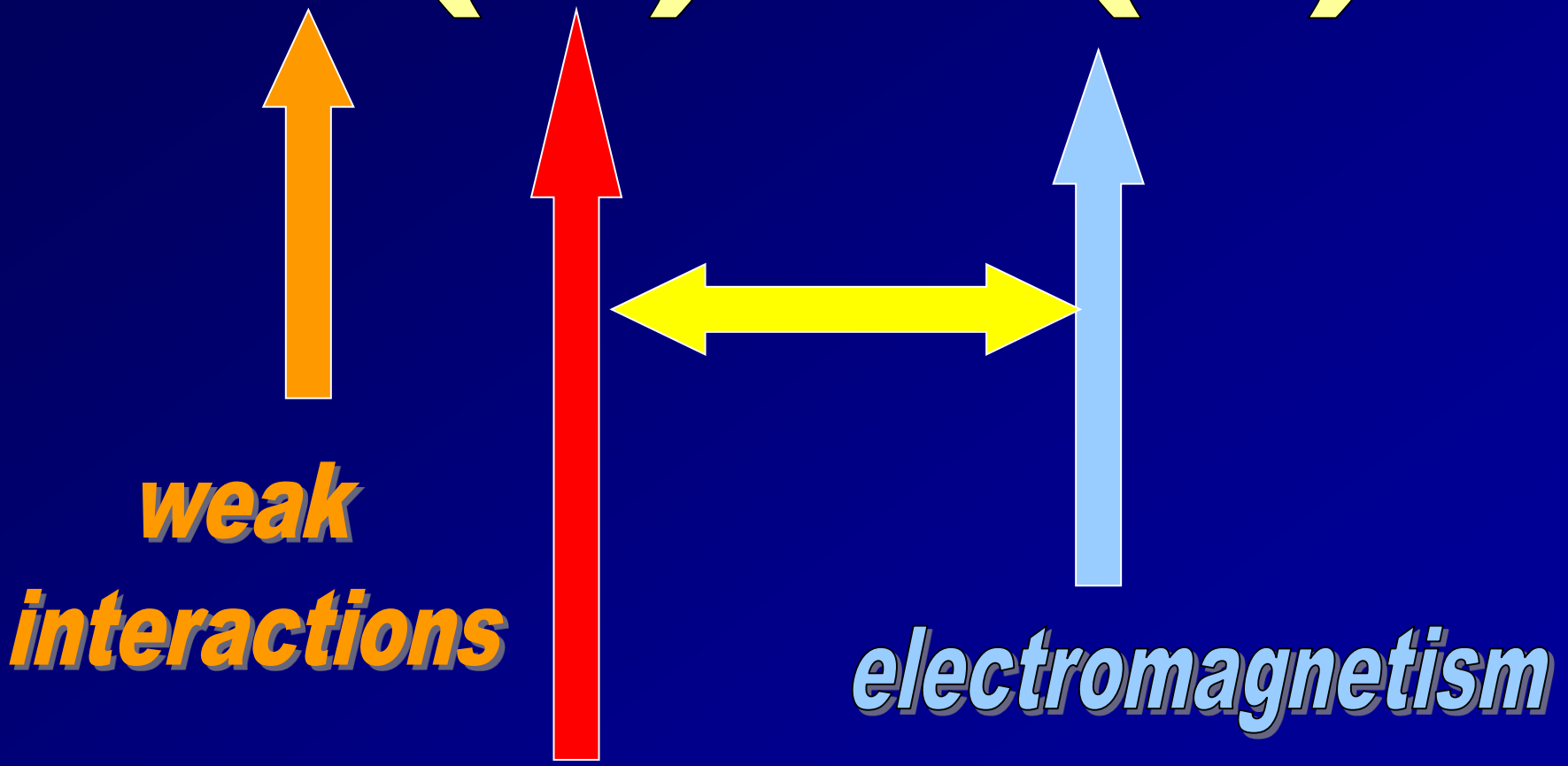
electroweak gauge theory



Glashow Salam Weinberg

1964-1968

SU(2)xU(1)



4 GAUGE BOSONS

W(+)

W(-)

Z

Photon

electroweak theory

5 CONSTANTS

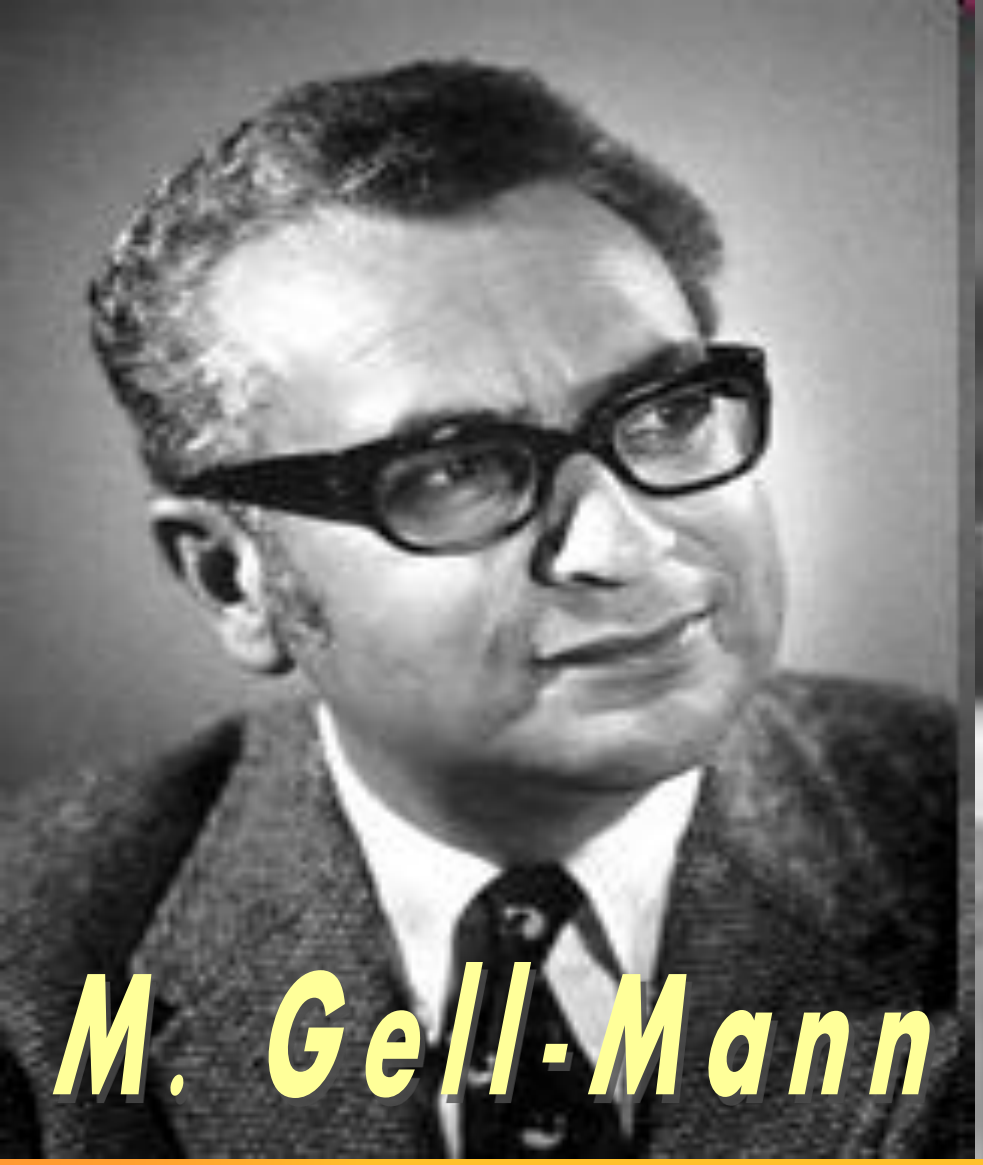
1 mass of weak boson

1 MASS OF "HIGGS" BOSON

2 coupling constants

1 electron mass

gauge theory of the Strong Interactions

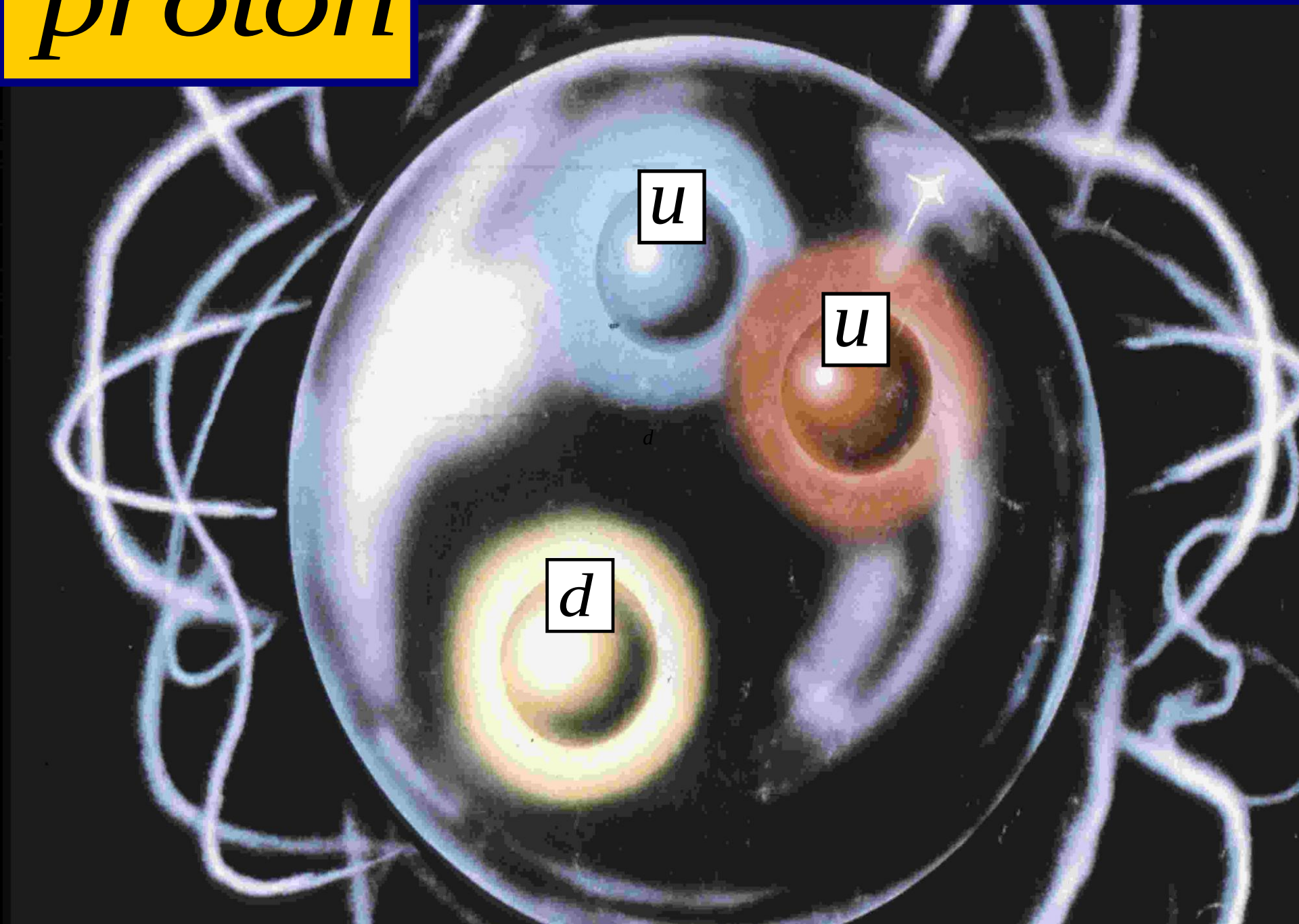


M. Gell-Mann

G. Zweig

1964 QUARKS

proton



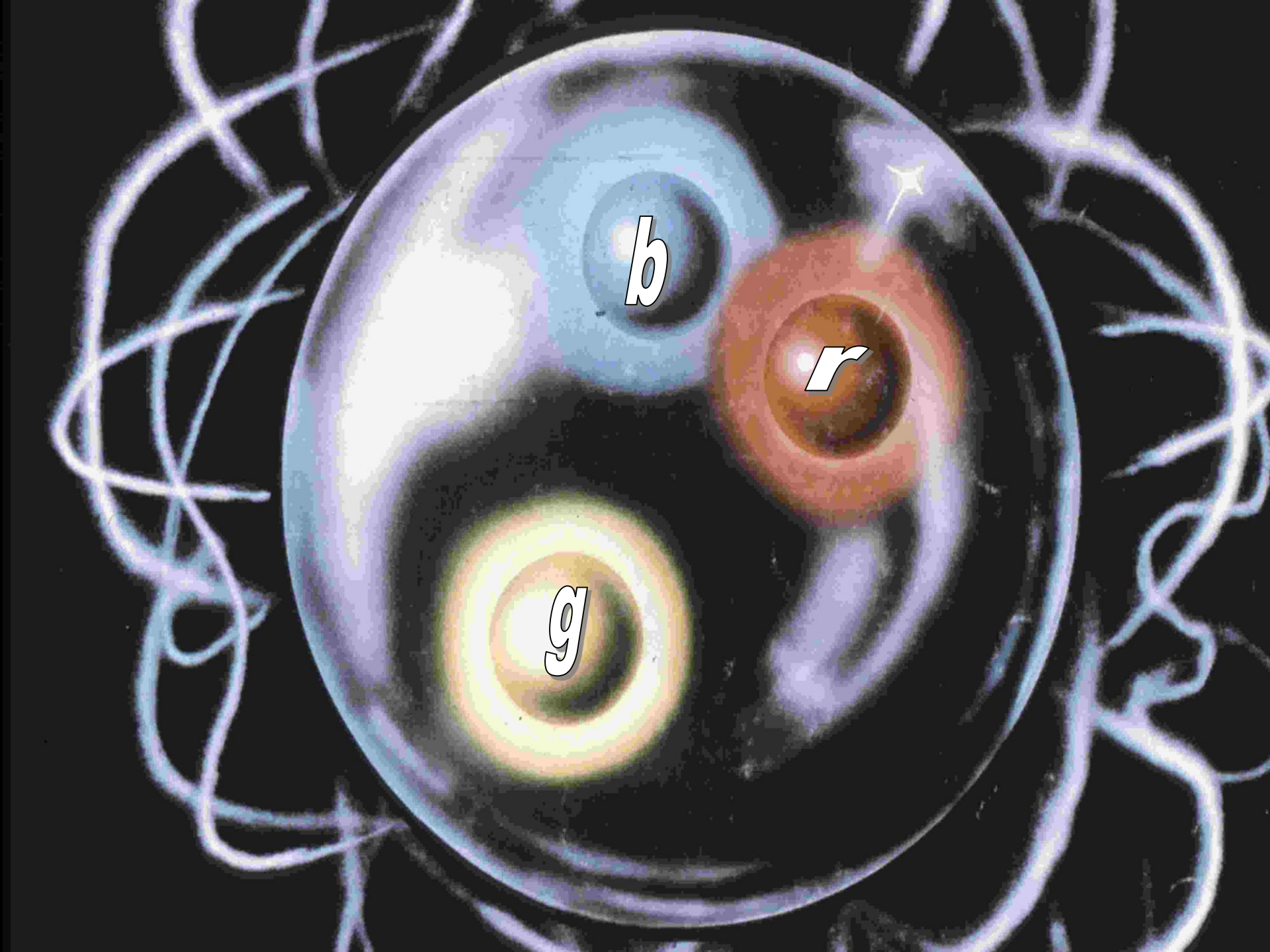
1971

color

q => q q q

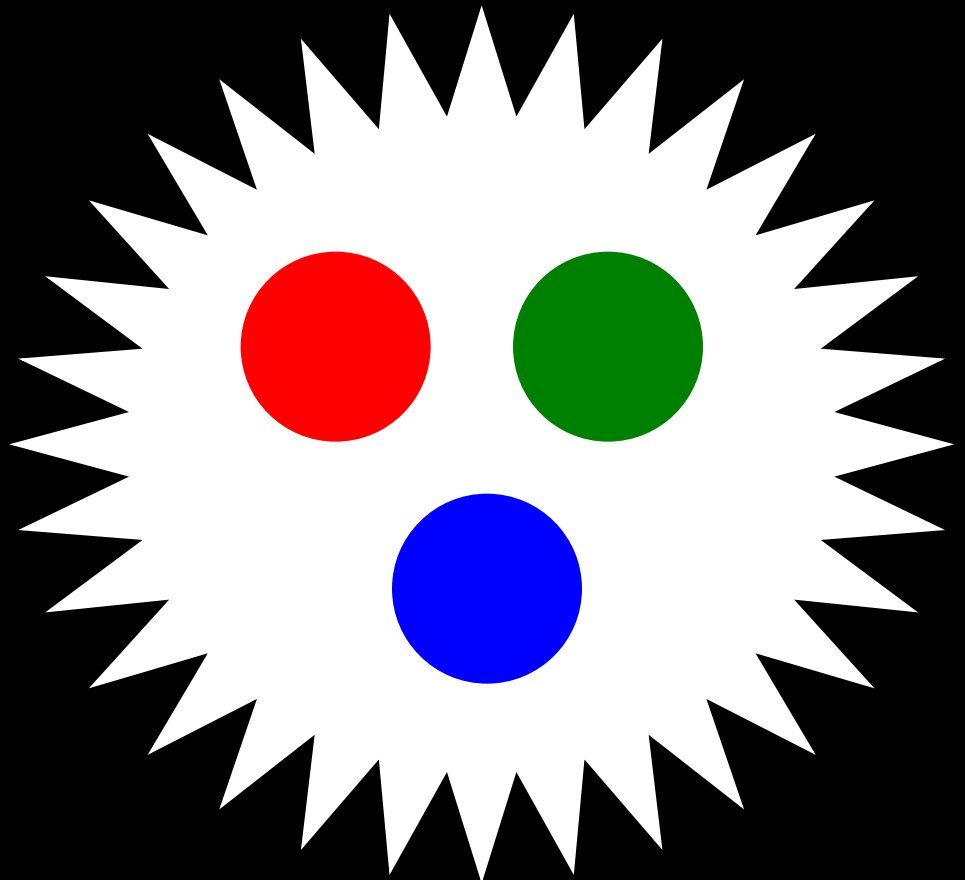
FRITZSCH / GELL-MANN

SU(3,c)


b
r
g

- Hadrons -

WHITE STATES



1972: Fritzsch / Gell-Mann

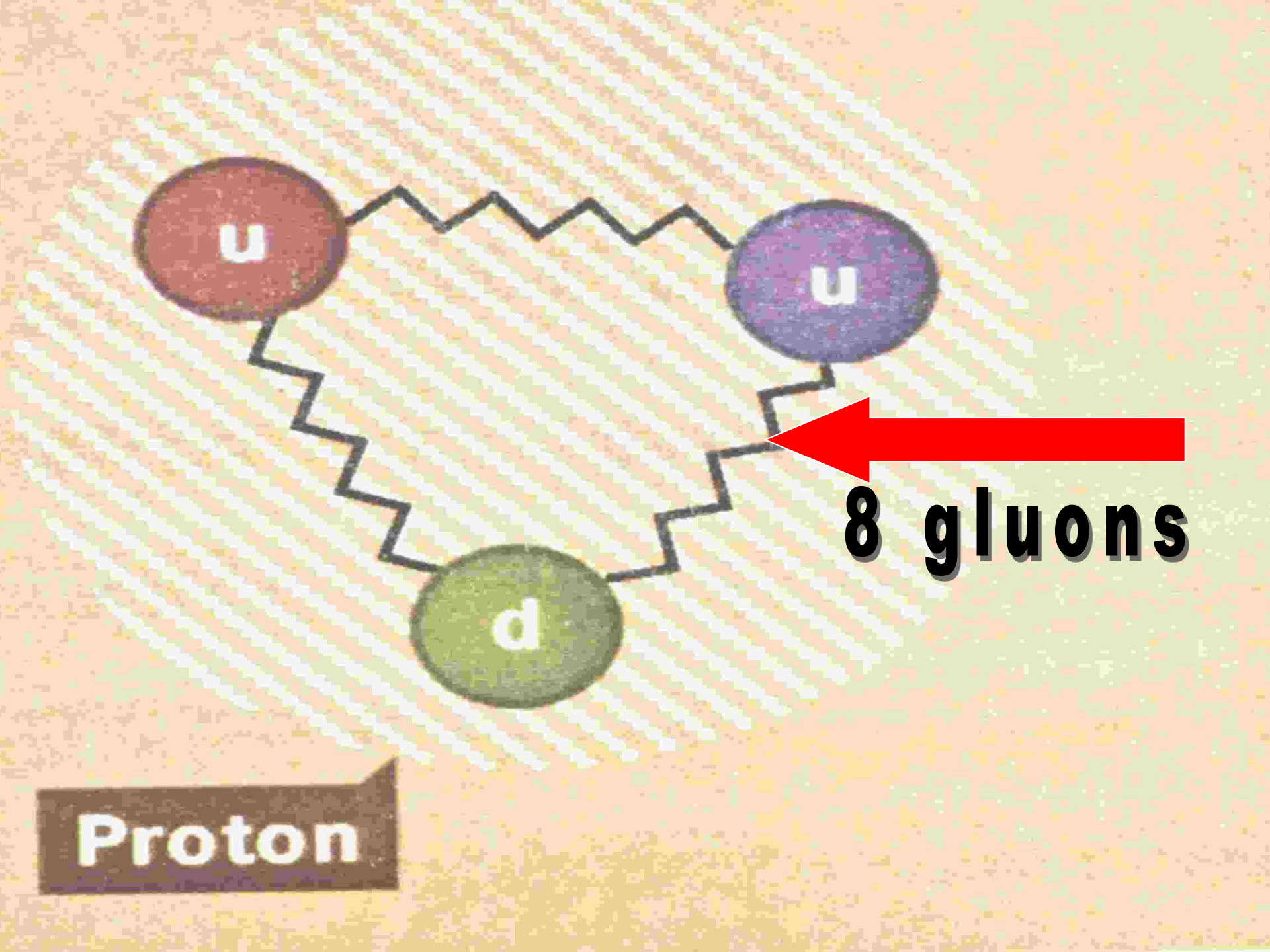
QCD

Quanten

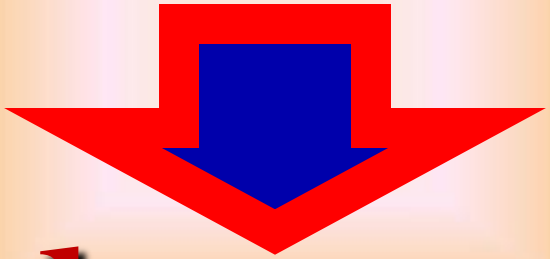
Chromo Dynamik

color group SU(3)

⇒ gauge group

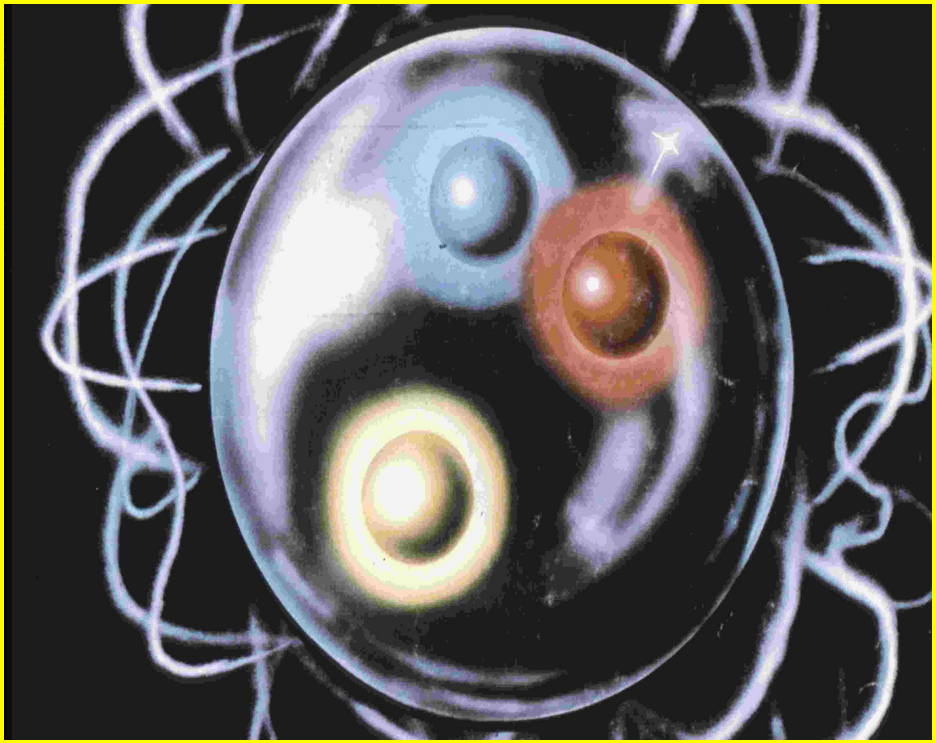

u
u
d
8 gluons
Proton

PROTON MASS



field energy

(gluons and quarks)



$$E(gluons) + E(quarks) = M_p c^2$$

70 % **30%**

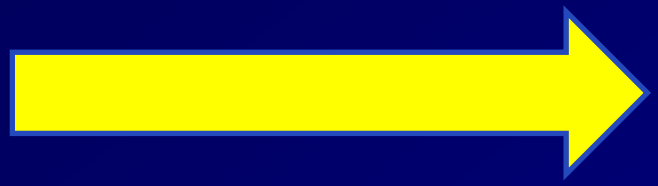
proton mass

(quark masses = 0)

$$M = const. \bullet \Lambda_c \approx 860\_MeV$$

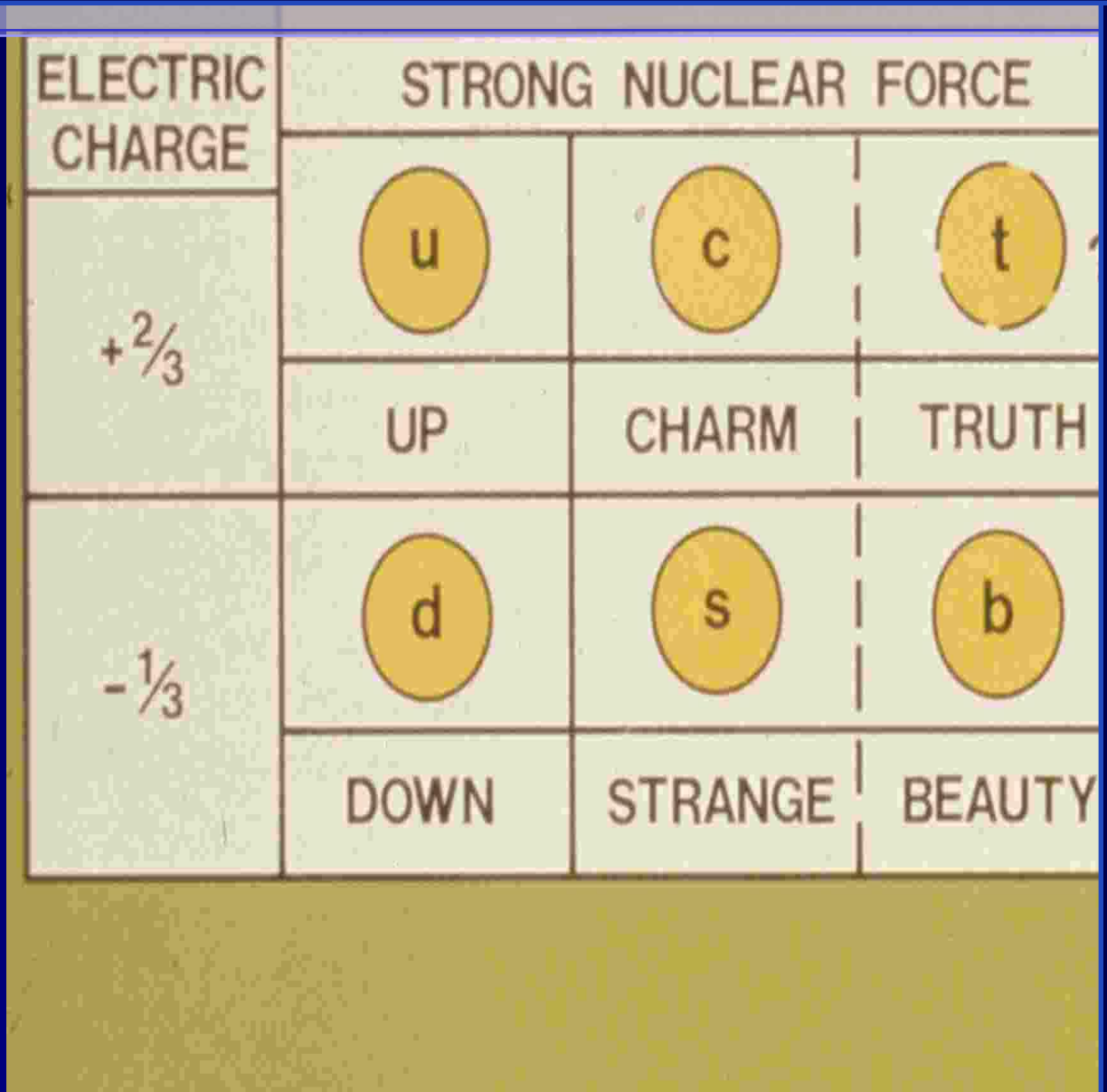
Λ_c ~ 250 MeV

lattice QCD



FUNDAMENTAL CONSTANT

$$\Lambda_c$$


ELECTRIC CHARGE
STRONG NUCLEAR FORCE
+2/3
u
c
t
UP
CHARM
TRUTH
-1/3
d
s
b
DOWN
STRANGE
BEAUTY

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

938 = 860 + 21 + 19 + 36 + 2

MeV

7 FUNDAMENTAL CONSTANTS IN STRONG INTERACTIONS

$$\Lambda_c$$

$$m_u \quad m_c \quad m_t$$

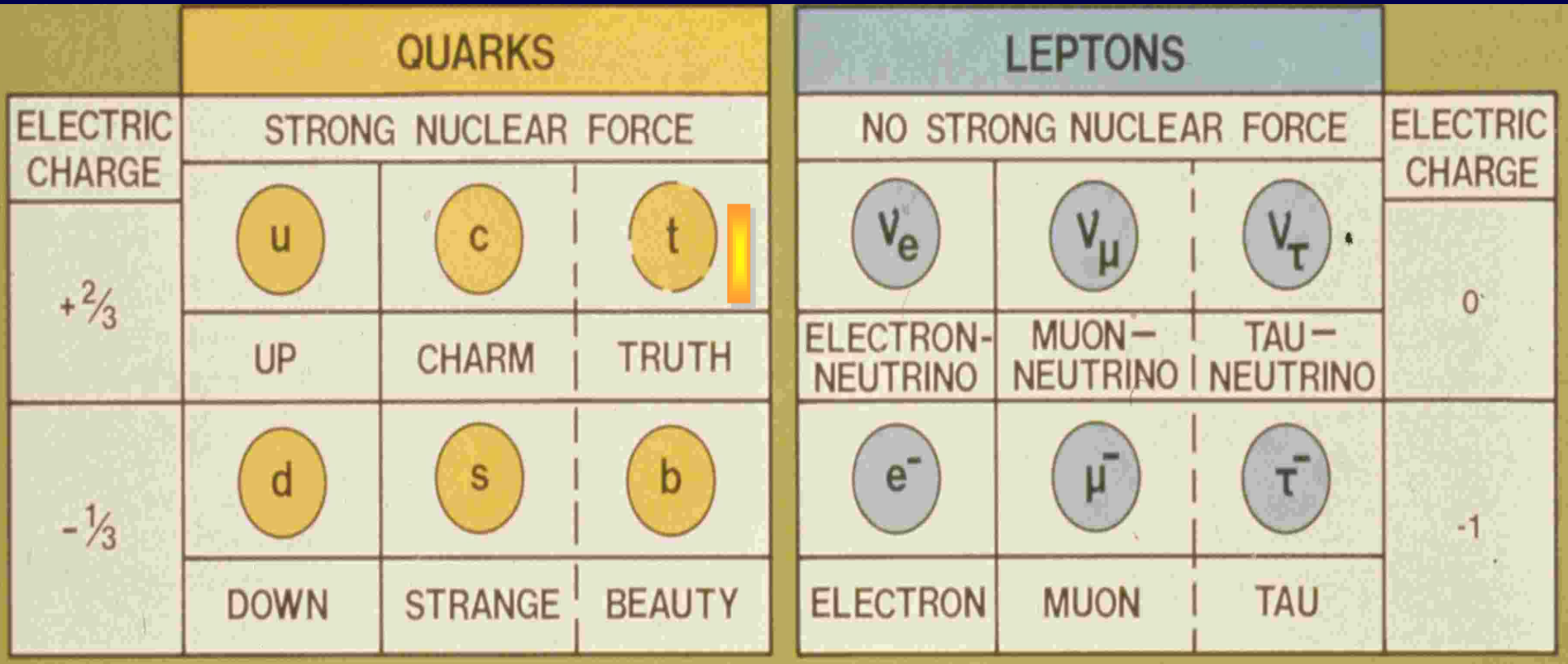
$$m_d \quad m_s \quad m_b$$

1973:

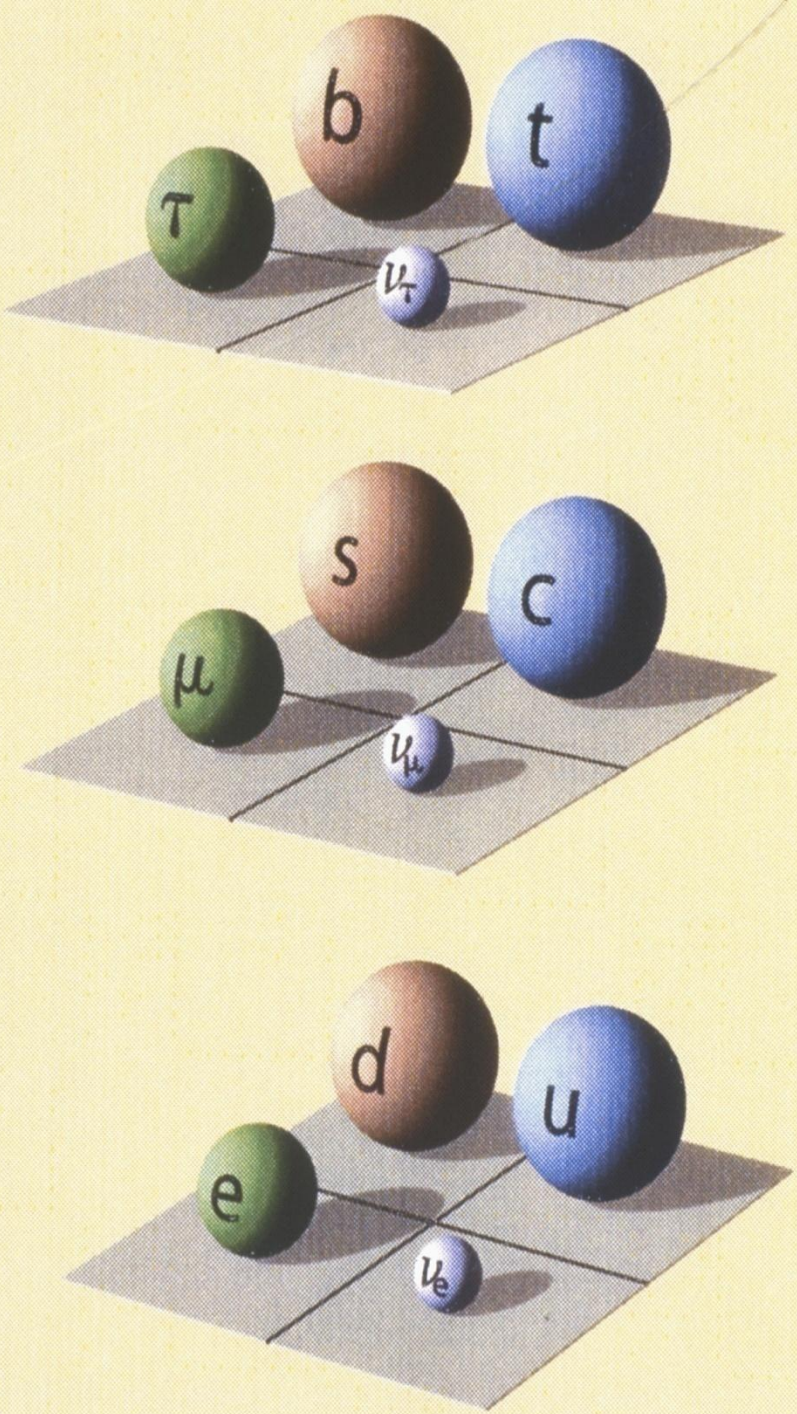
Standard Model

SU(3) x SU(2) x U(1)

The Standard Model



3 families of leptons and quarks.



THREE DIMENSIONS

THREE COLORS

THREE FAMILIES

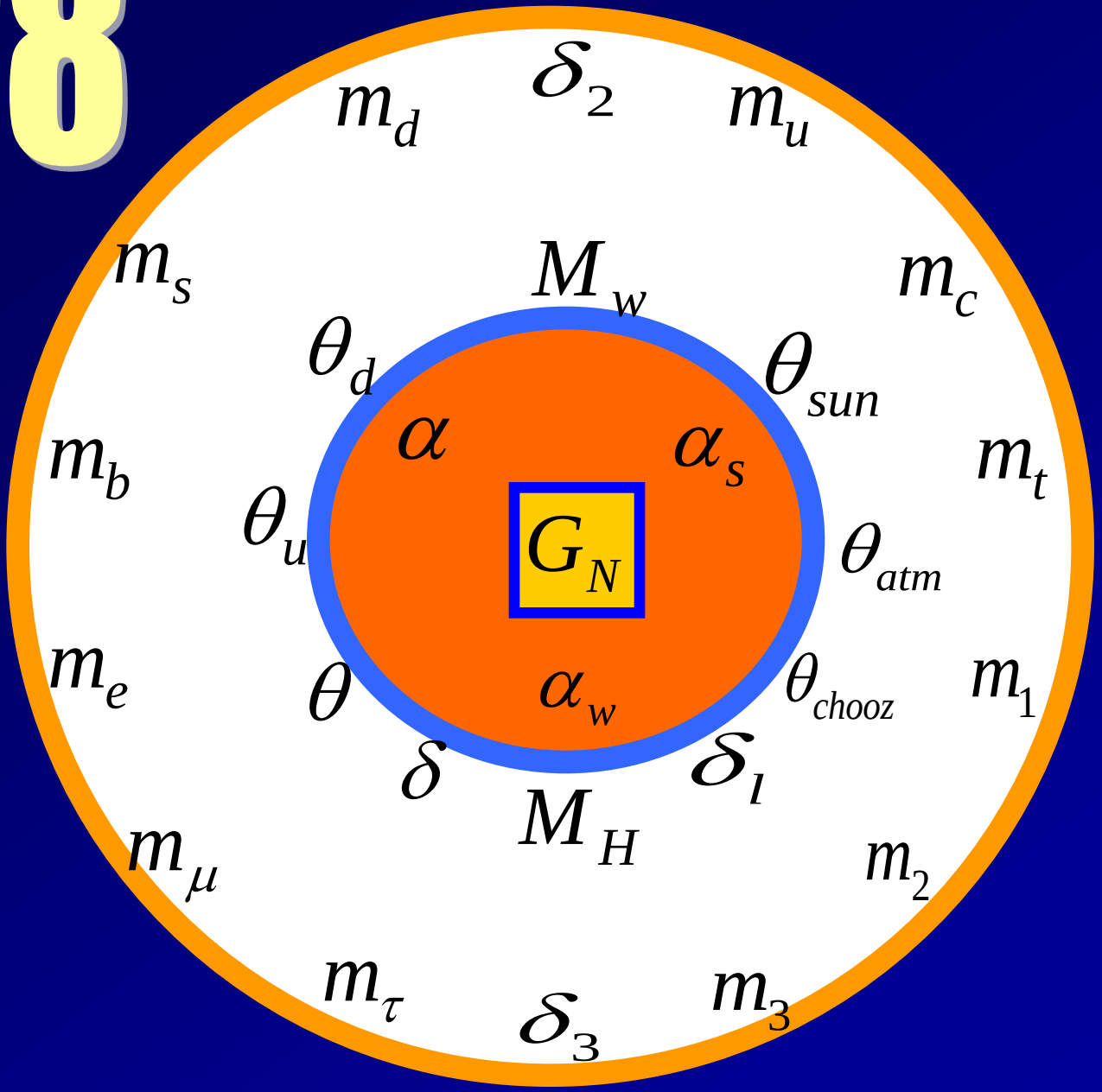
Johannes Paul II

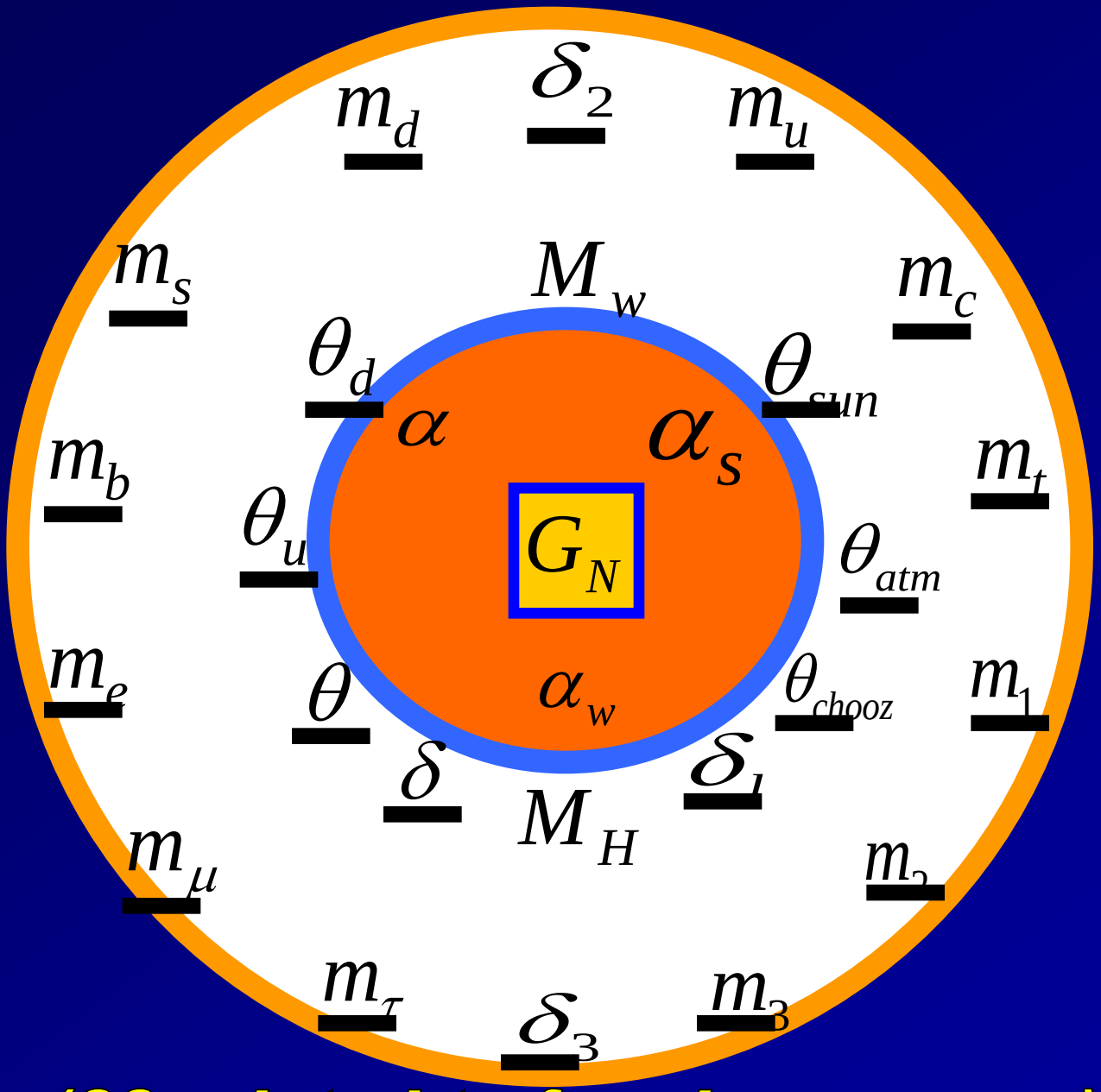
= = = > problem

28 fundamental constants

Newtons constant G	1
fine structure constant	1
coupling constant of strong interaction	1
coupling constant of weak interaction	1
mass of W boson	1
mass of Higgs boson	1
masses of 6 quarks and 6 leptons	12
flavor mixing of quarks	4
flavor mixing of leptons	6

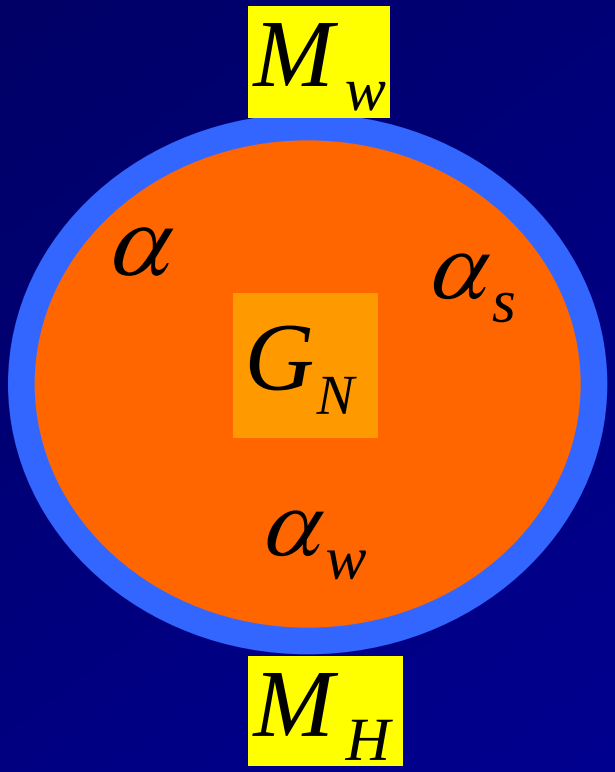
28


δ_2
m_d
m_u
m_s
M_w
m_c
θ_d
θ_{sun}
α
α_s
m_b
m_t
θ_u
G_N
θ_{atm}
m_e
θ
α_w
θ_{chooz}
m_1
δ
δ_1
M_H
m_μ
m_2
m_τ
δ_3
m_3

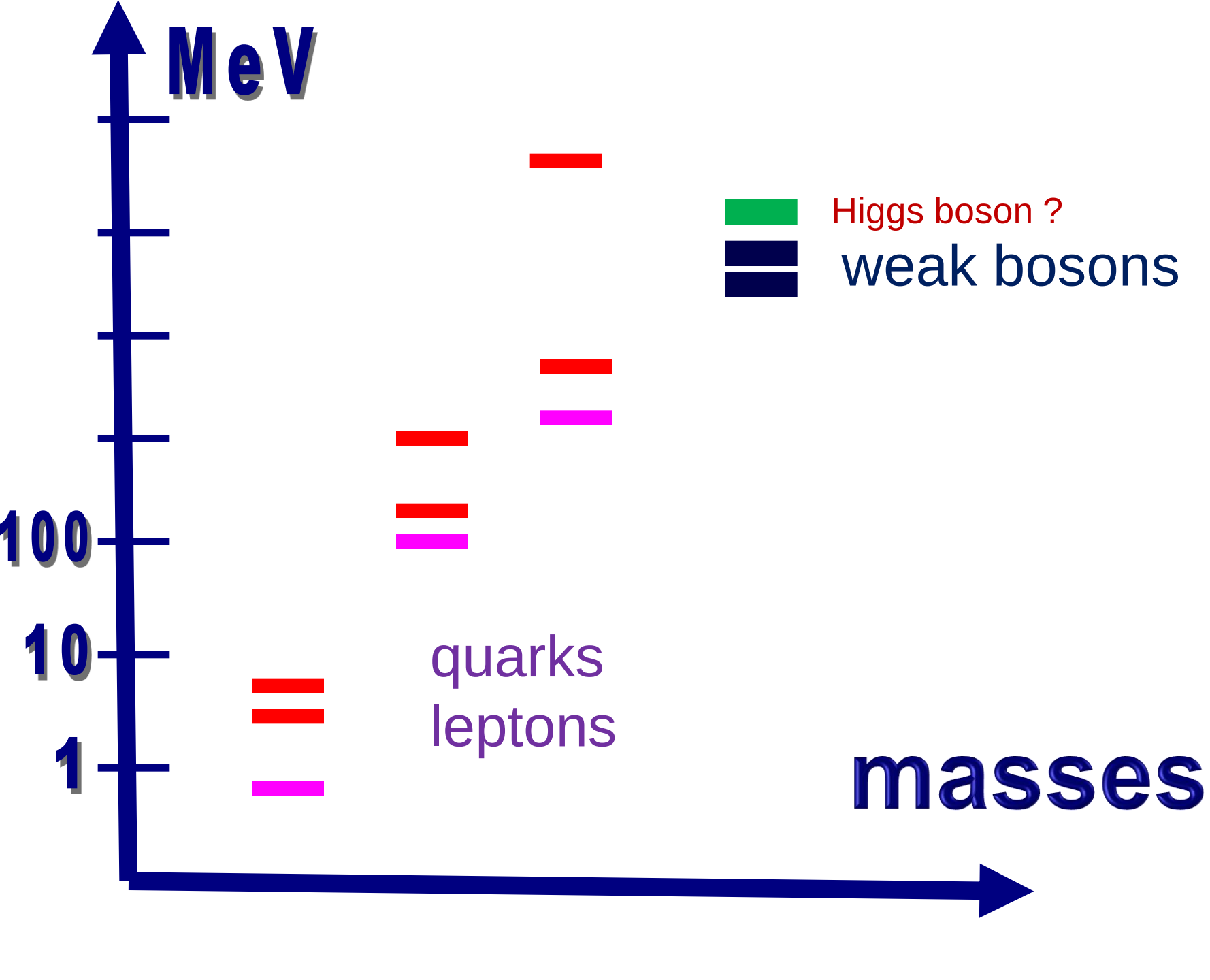


(22 related to fermion masses)

fermion masses = 0

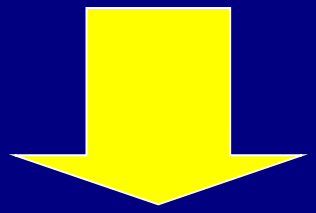


6 constants


MeV
100
10
1
Higgs boson ?
weak bosons
quarks
leptons
masses

Standard Model:

fundamental constants in our universe



universal

Are the fundamental constants

FUNCTIONS OF TIME AND SPACE?

OKLO PHENOMENON

➔ 1.8 billion years

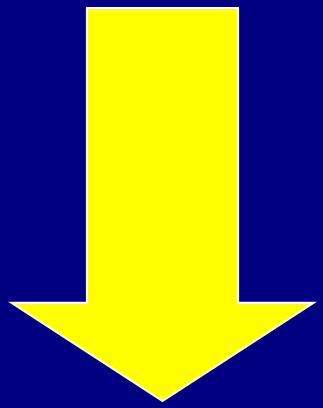
(Gabon, Africa)

Natural Reactor

3.7% U 235 (today 0.72 %)

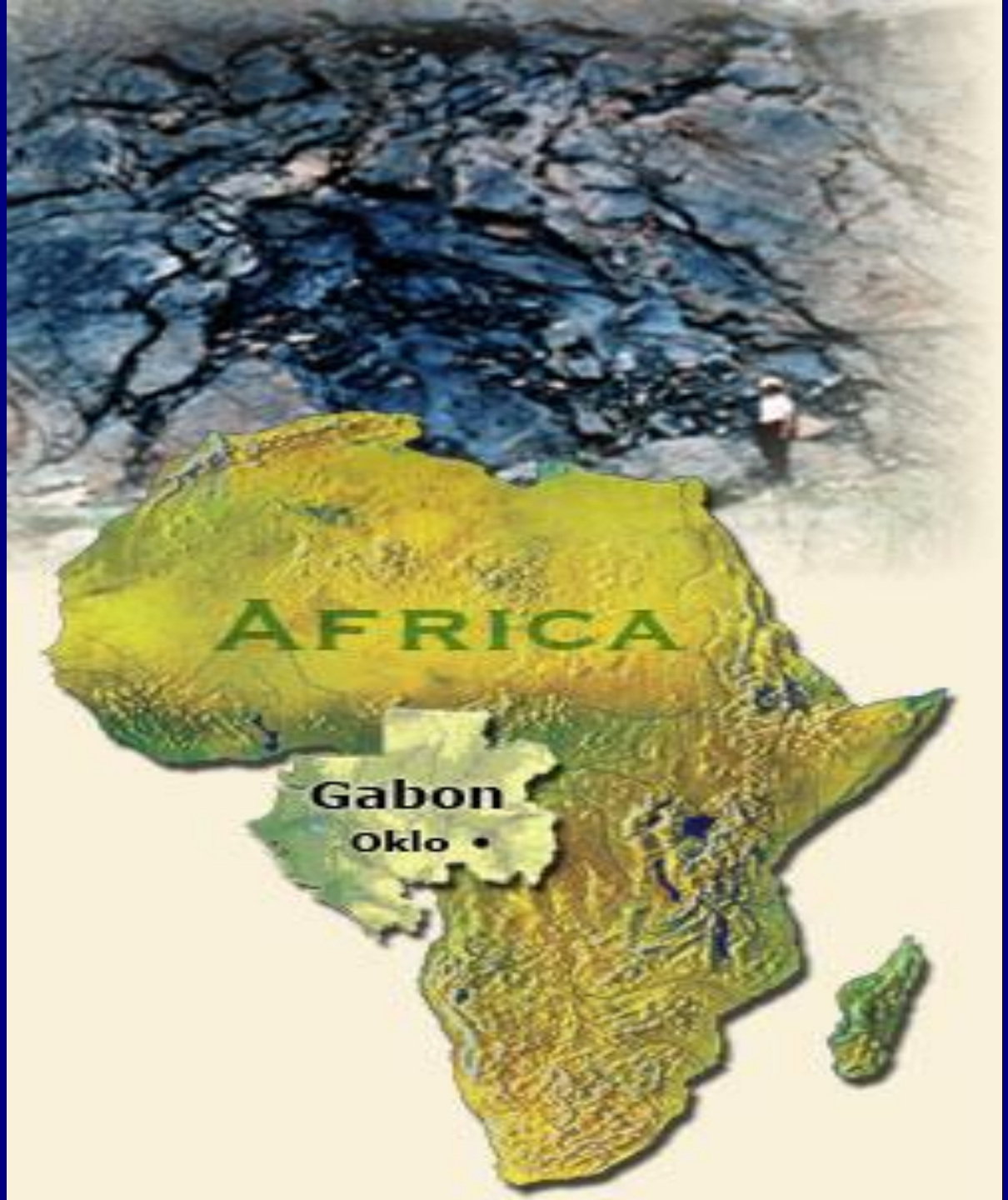
Moderator: water from river Oklo

discovery: 1972



Natural reactor

(output: ~ 100 kw)


AFRICA
Gabon
Oklo


CAMEROON
Atlantic
Ocean
GABON
Libreville
0°
CONGO
Port
Gentile
OKLO
Mounana
Franceville
10° E
200 km

samarium:

neutron capture

$$Sm(149) + n \Rightarrow Sm(150) + photon$$

cross section about 80 kb

nuclear resonance: E = 0.0973 eV

change of resonance position less than 0.1 eV in 2 billion years

constraint for fine-structure constant:

$$\left(\frac{\alpha(Oklo) - \alpha(now)}{\alpha} \right) \leq 10^{-7}$$

(Dyson, Damour)

Change of alpha:

$$\dot{\alpha} / \alpha \leq 10^{-16} / year$$

(if no other parameters change)

???

Time Variation of alpha?

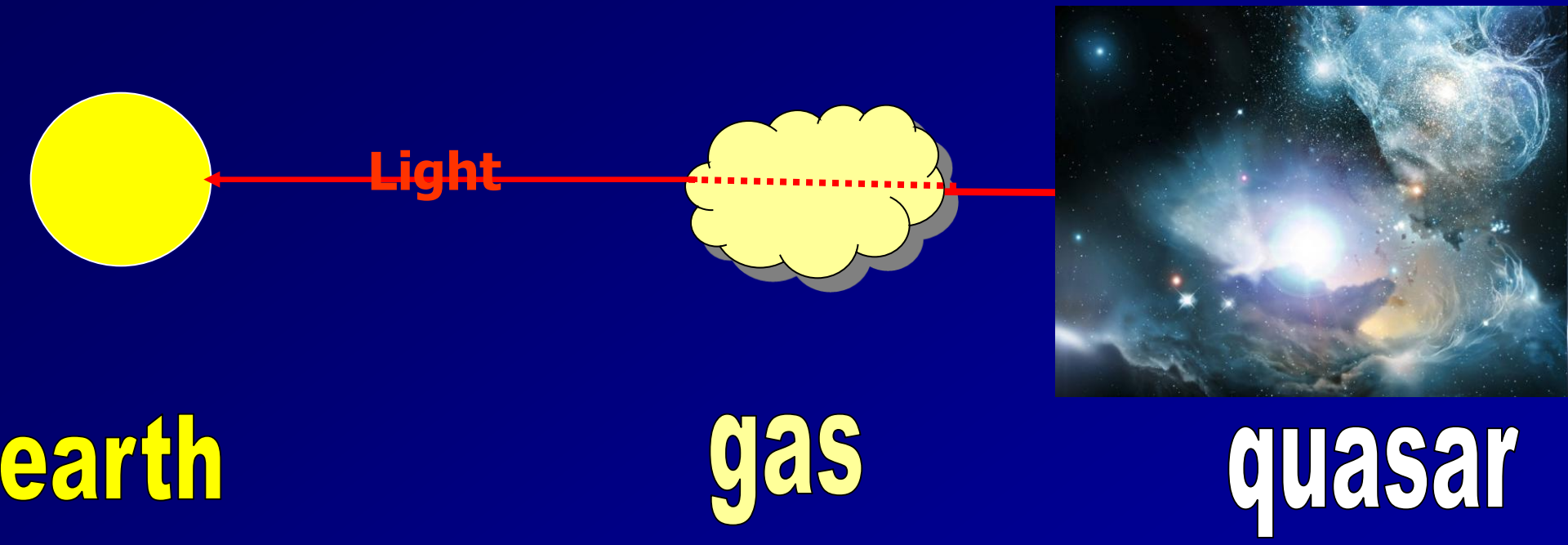
Observation :

fine - structure of atomic levels

Quasars

5-7 billion years back

Quasar absorption spectra



Keck telescope

Keck telescope

Hawaii

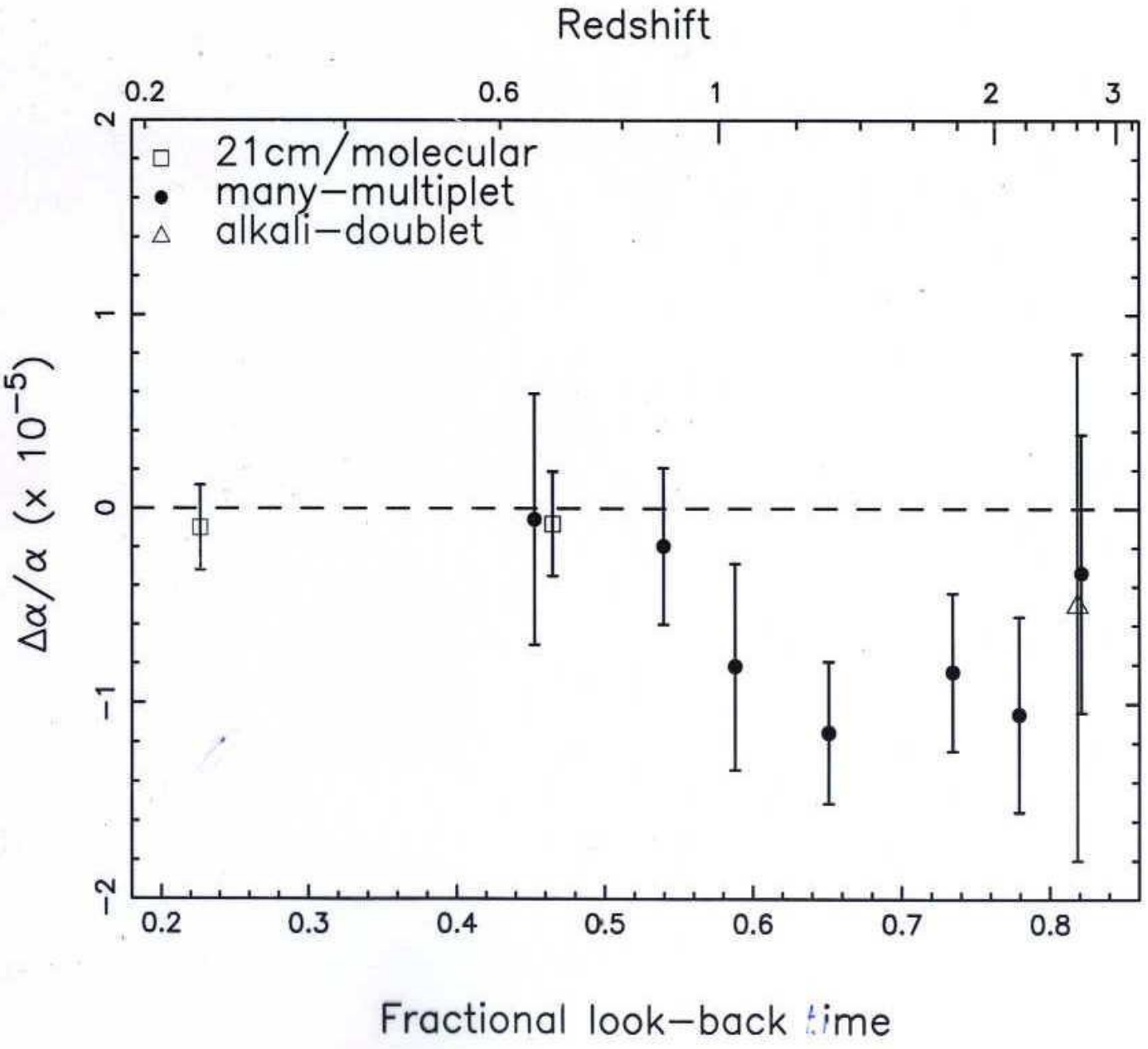
Experiment at Keck telescope (Australia, England, USA)

(Webb, Wolf, Flambaum...)

Fine structure of Fe, Ni, Mg, Sn, A -
Quasars, back to 11 bn years in time

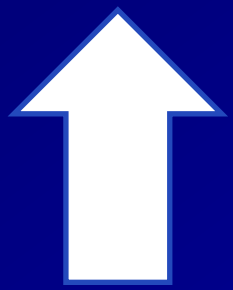
$$\Delta\alpha/\alpha = (-0.54 \pm 0.12)10^{-5}$$

$$\Rightarrow \dot{\alpha}/\alpha \approx 1.2 \cdot 10^{-15} / year$$


Redshift
0.2
0.6
1
2
3
21cm/molecular
many−multiplet
alkali−doublet
$\Delta\alpha/\alpha$ (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

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

$$\Rightarrow \dot{\alpha}/\alpha \approx 1.2 \cdot 10^{-15} / year$$



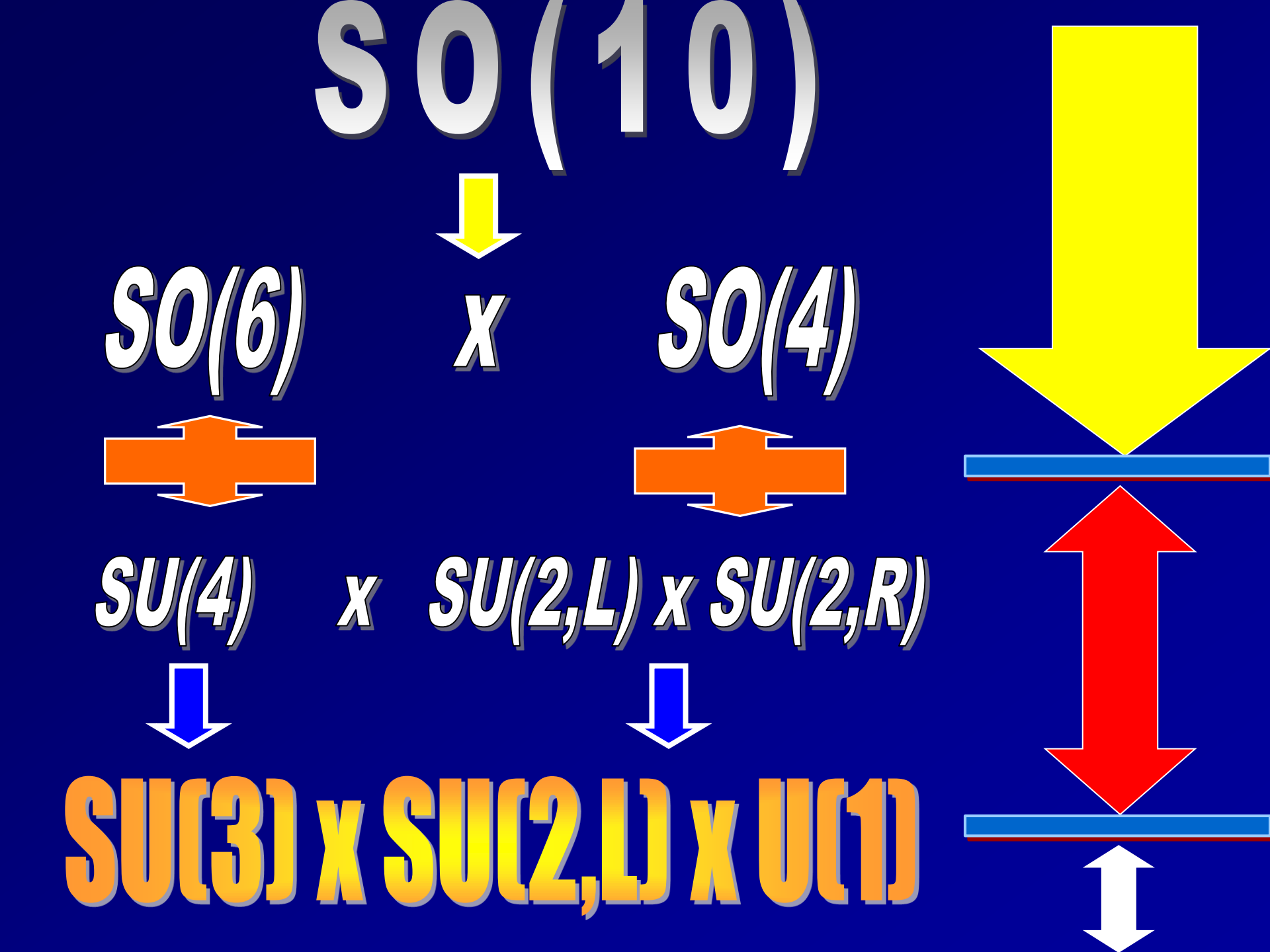
OKLO REACTOR ?

grand unification:

SU(3)xSU(2)xU(1)

==>SO(10)

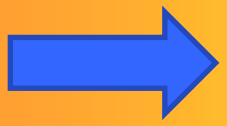
(Fritzsch - Minkowski; Georgi - 1975)


SO(10)
SO(6) x SO(4)
SU(4) x SU(2,L) x SU(2,R)
SU(3) x SU(2,L) x U(1)

Grand Unification

3 coupling constants

electromagnetic - weak - strong interactions



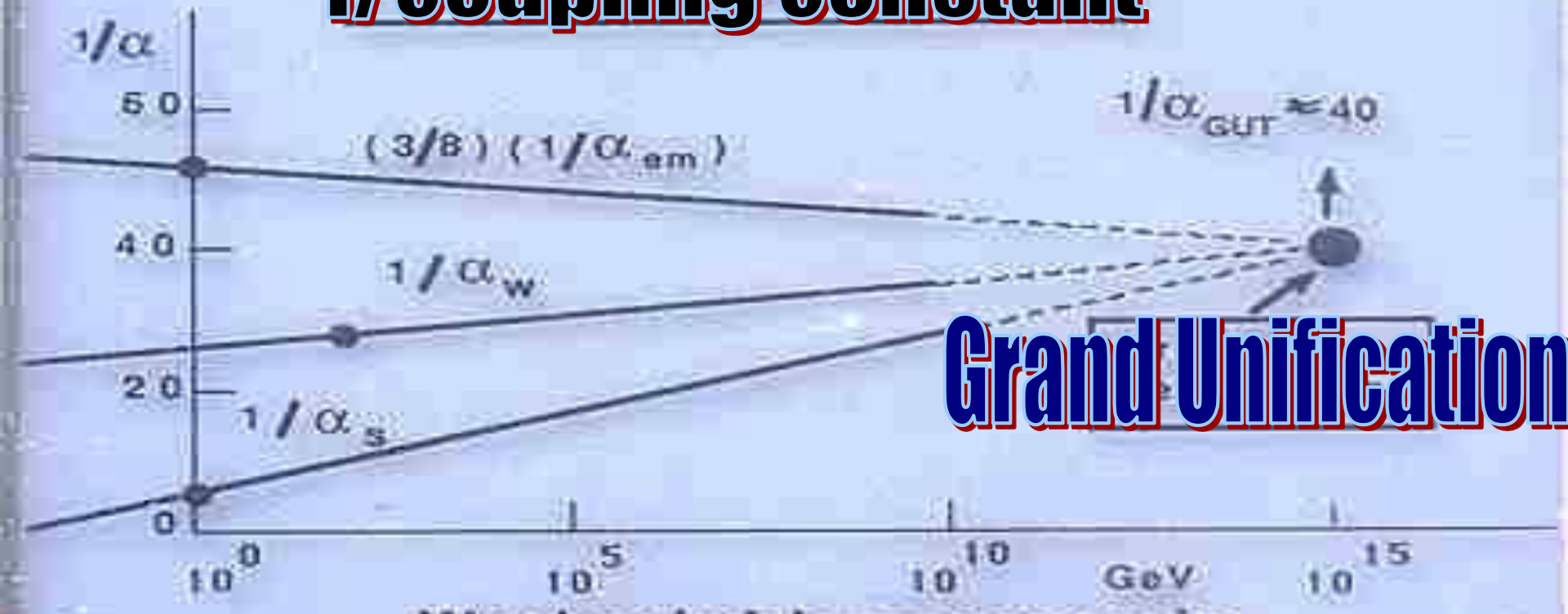
two parameters

unification scale

–

unified coupling

1/coupling constant

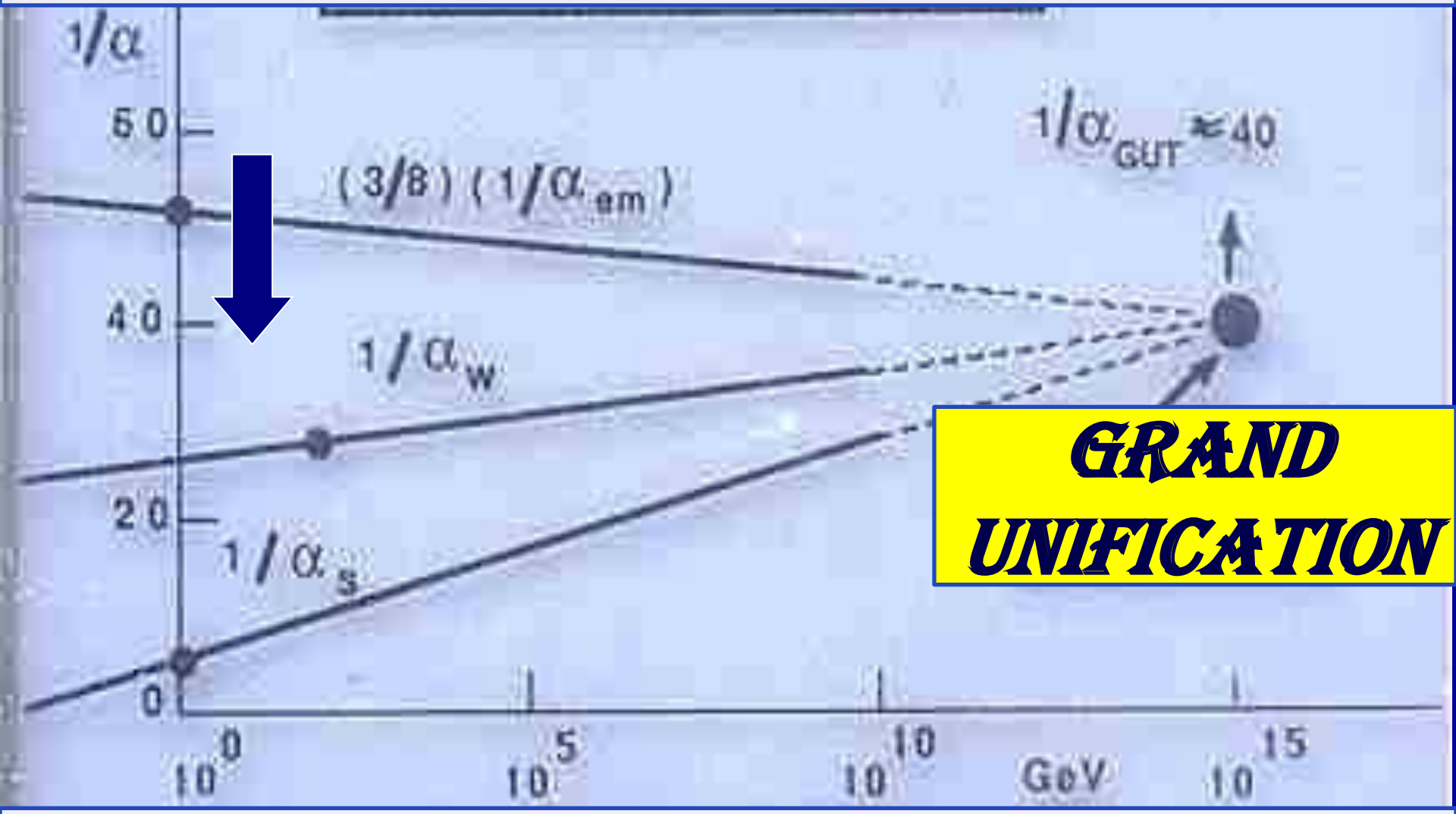


Grand Unification

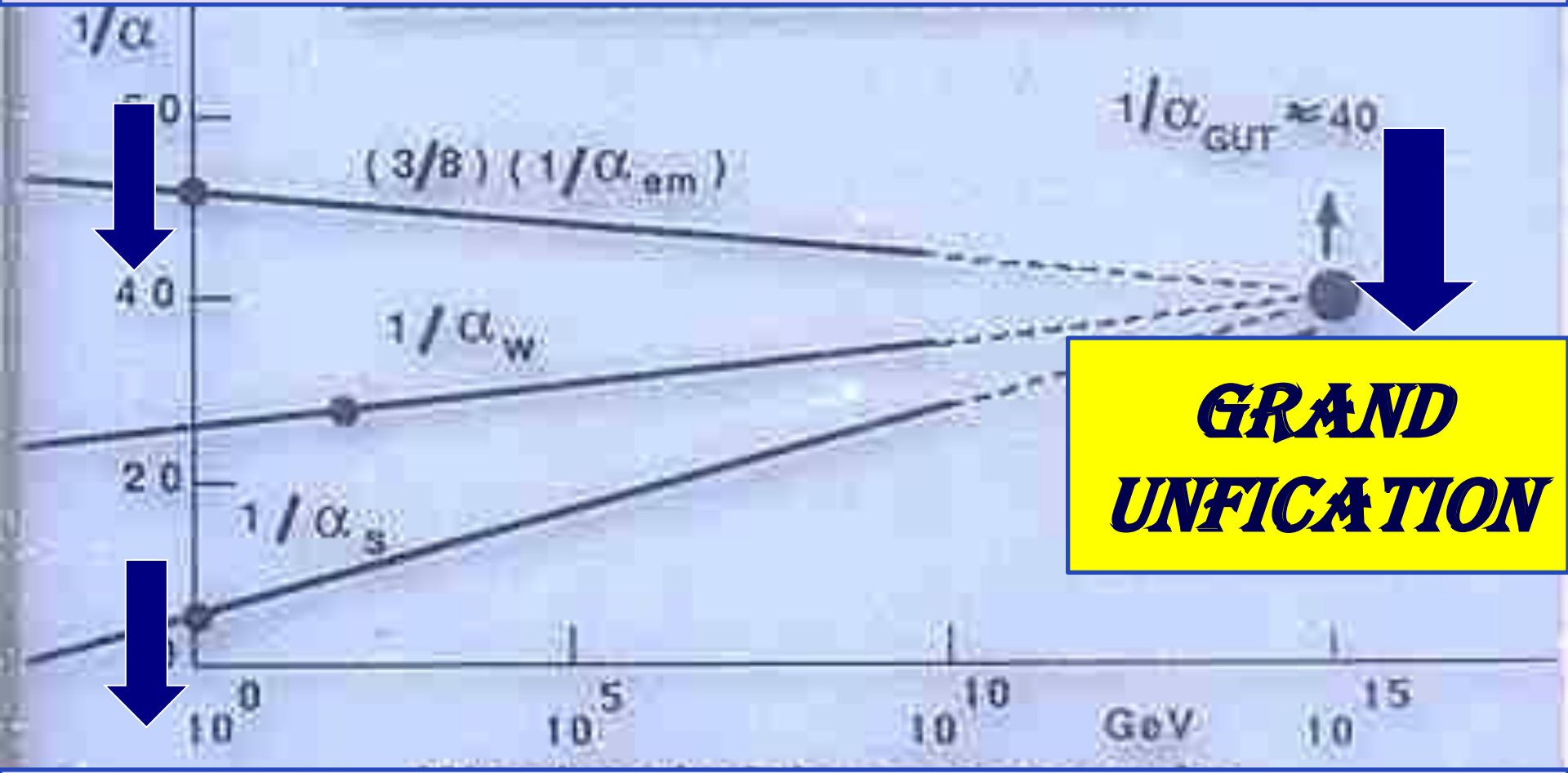
energy

time change of

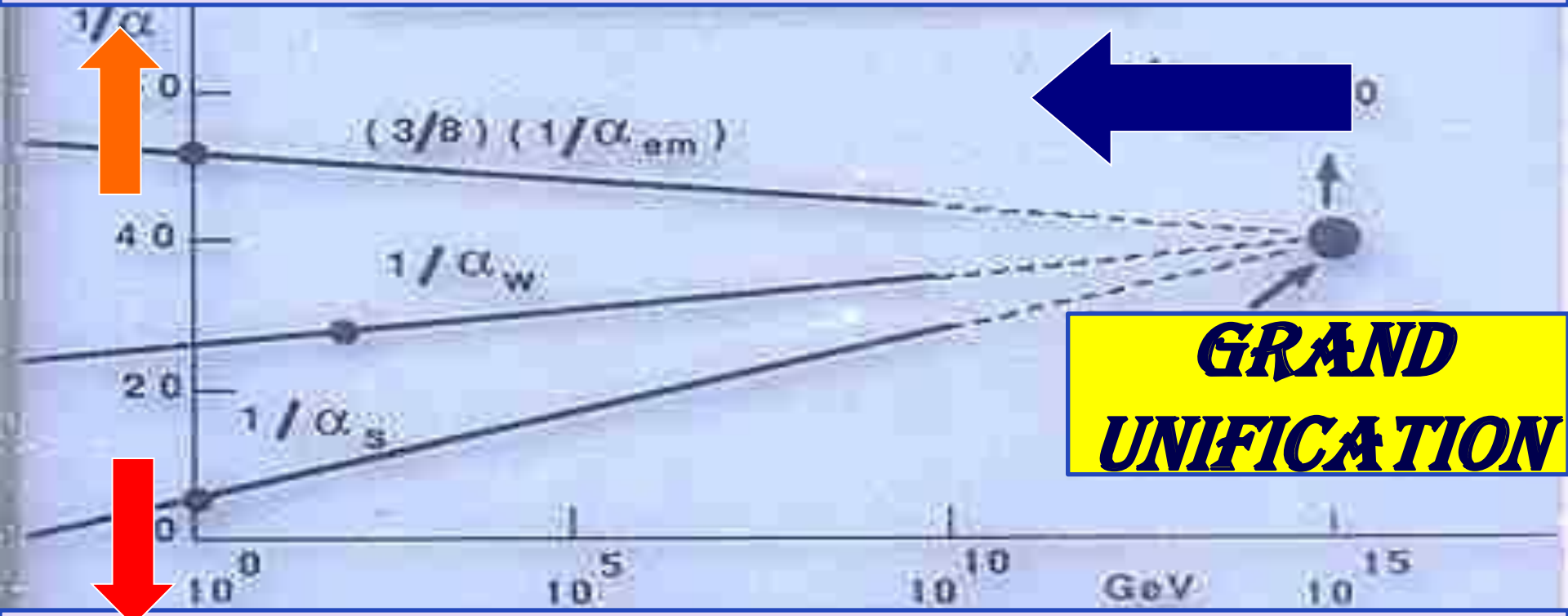
α ?



GRAND UNIFICATION



GRAND UNFICATION

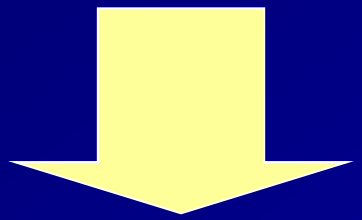

1/α
60
40
20
0
(3/8) (1/α em)
1/α w
1/α s
10^0
10^5
10^10
GeV
10^15
GRAND
UNIFICATION

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

Calmet, Fritzsch
Langacker, Segre
(2002)

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

no change of unification scale



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

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

change of magnetic moments of atomic nuclei (per year)

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

Change of unification scale:

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

$$change \quad of \quad \alpha :\sim 10^{-15} / year$$

$$change \quad of \quad \Lambda :\sim 10^{-14} / year$$

experiments

MPQ MUNICH

NIST BOULDER

TIME

=> Cesium clocks

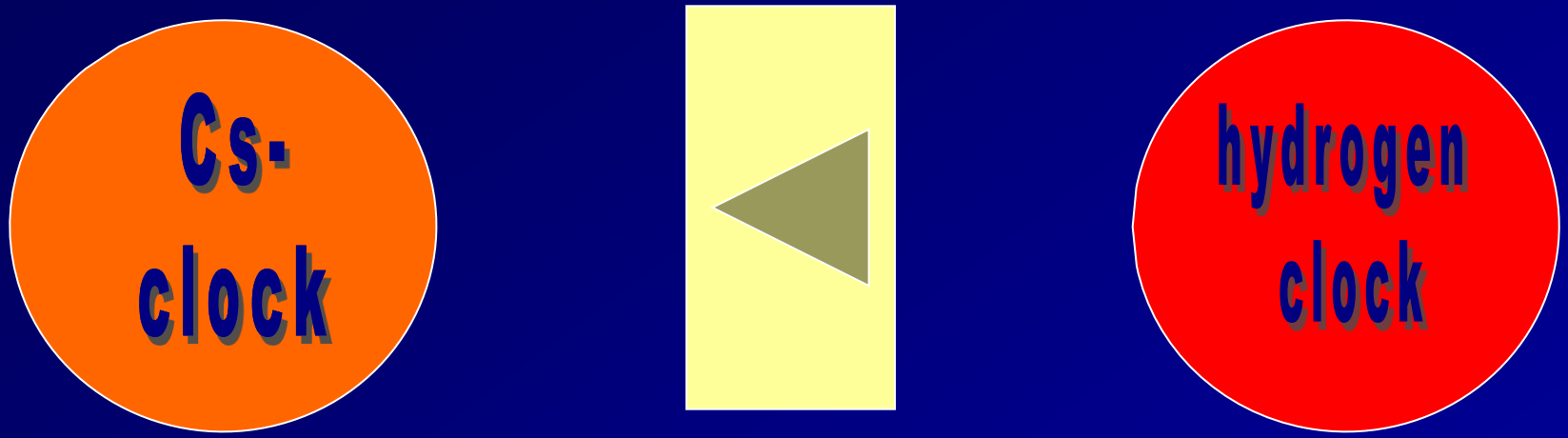
Hyperfine transition

➔ MAGNETIC MOMENT OF CESIUM NUCLEUS

Cesium: 9 192 631 770 Hz

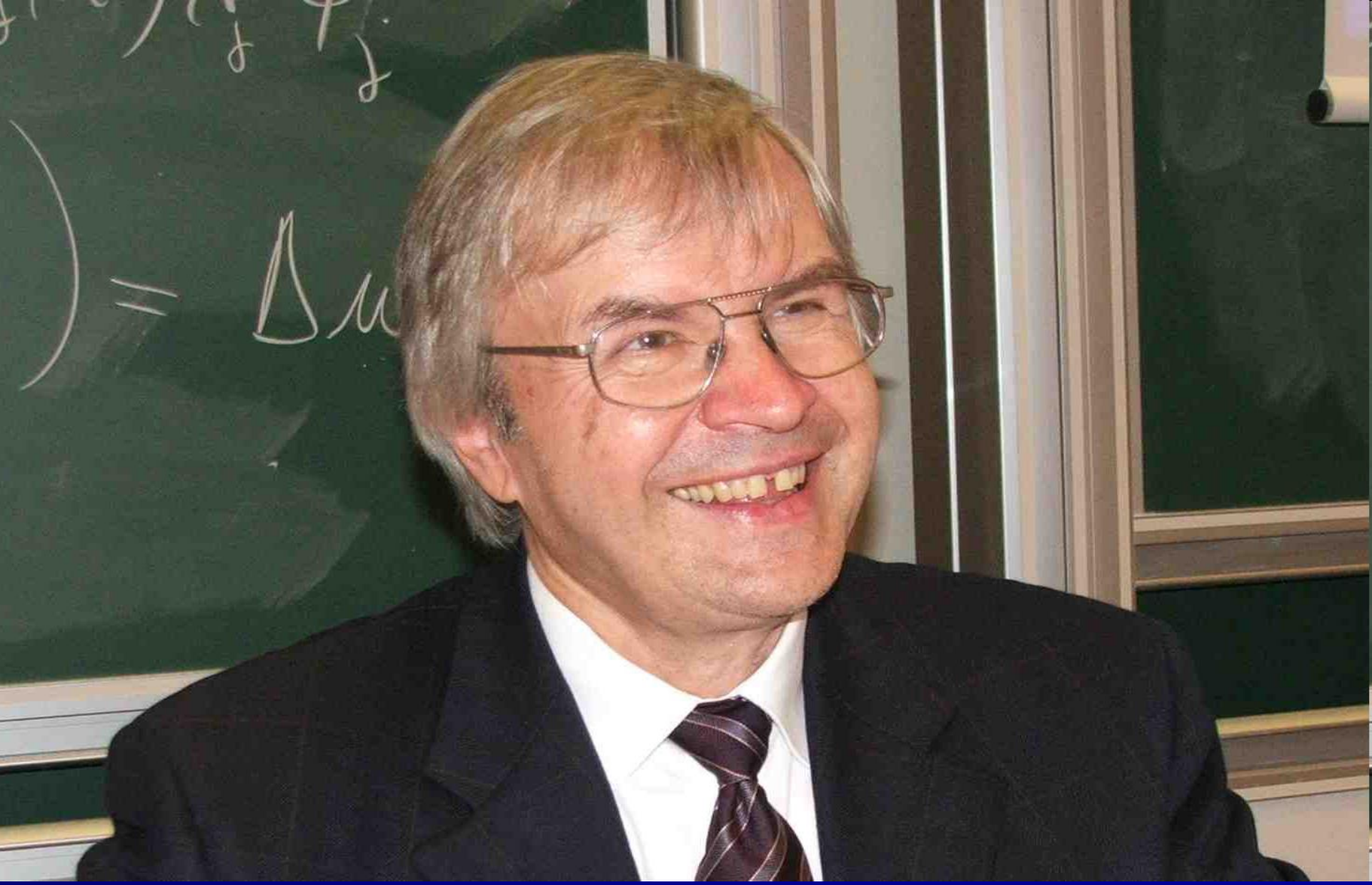
(definition of time)

comparison:



Difference: 3 CS oscillations per day

Experiment
(T. Hänsch, MPQ)



T. Hänsch

Nobel prize 2006

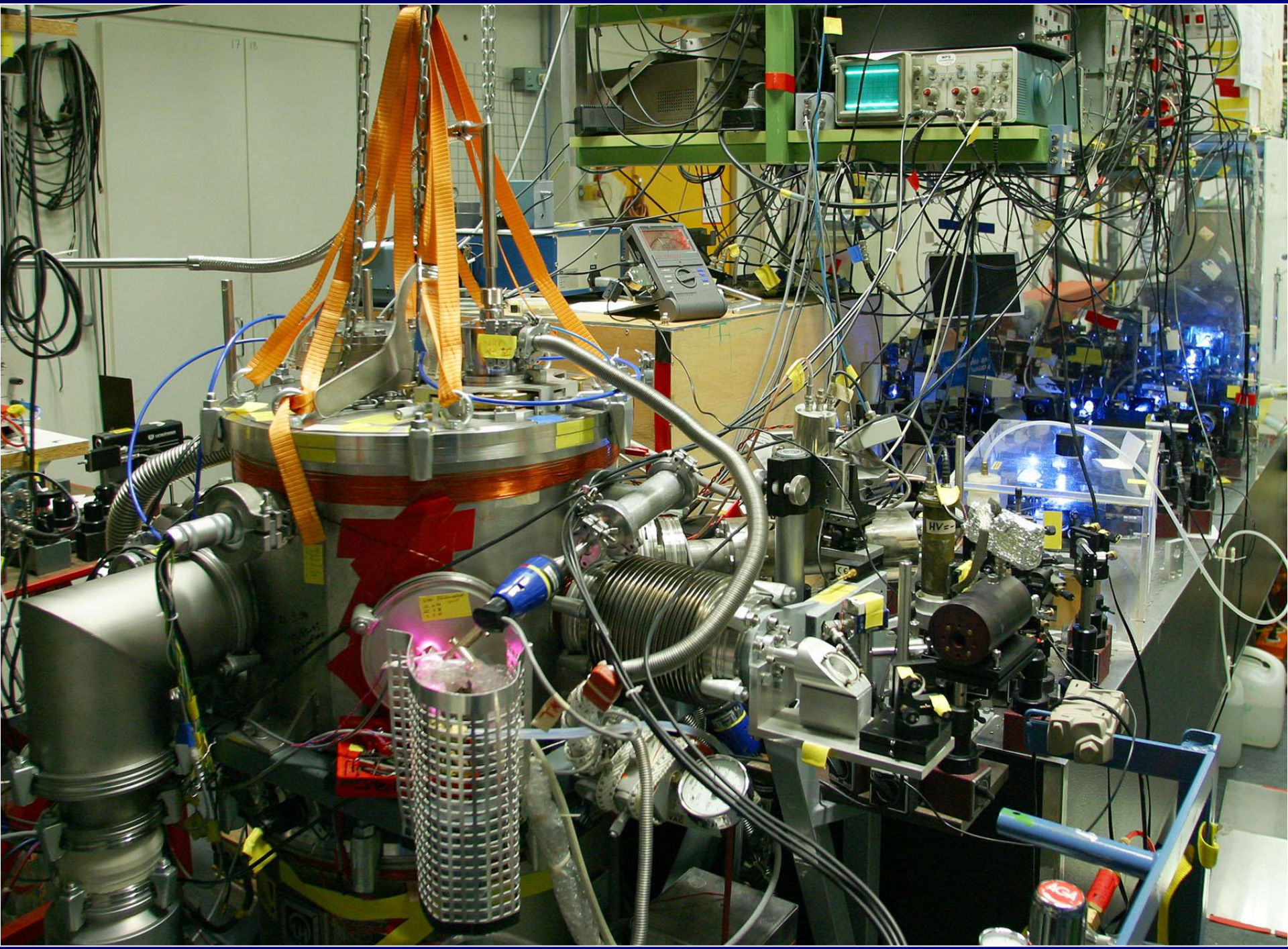
MPQ-experiment

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



μ: magnetic moment

$$\dot{\Lambda} / \Lambda = \dot{\mu} / \mu$$

Haensch:

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

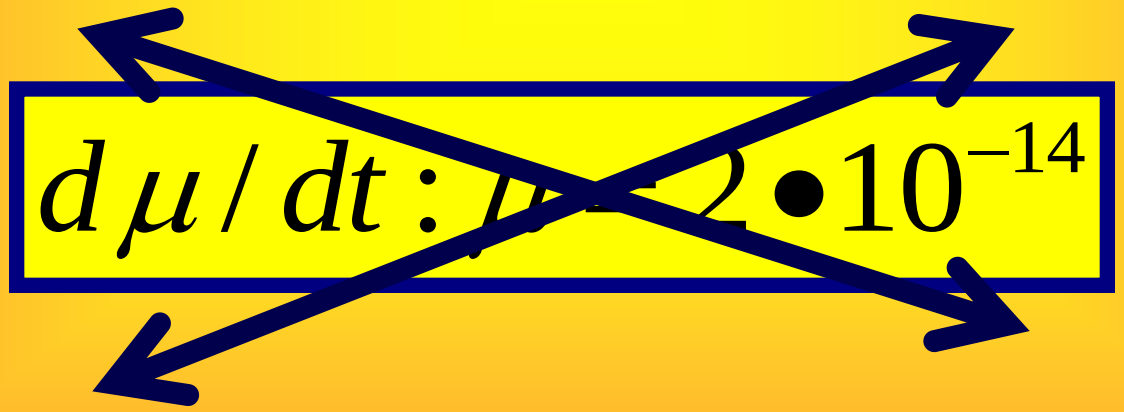
$$d\mu/dt : \mu = (2.4 \pm 6.8) \bullet 10^{-15}\, yr^{-1}$$

expected:

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

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

expected:



Simultaneous change:

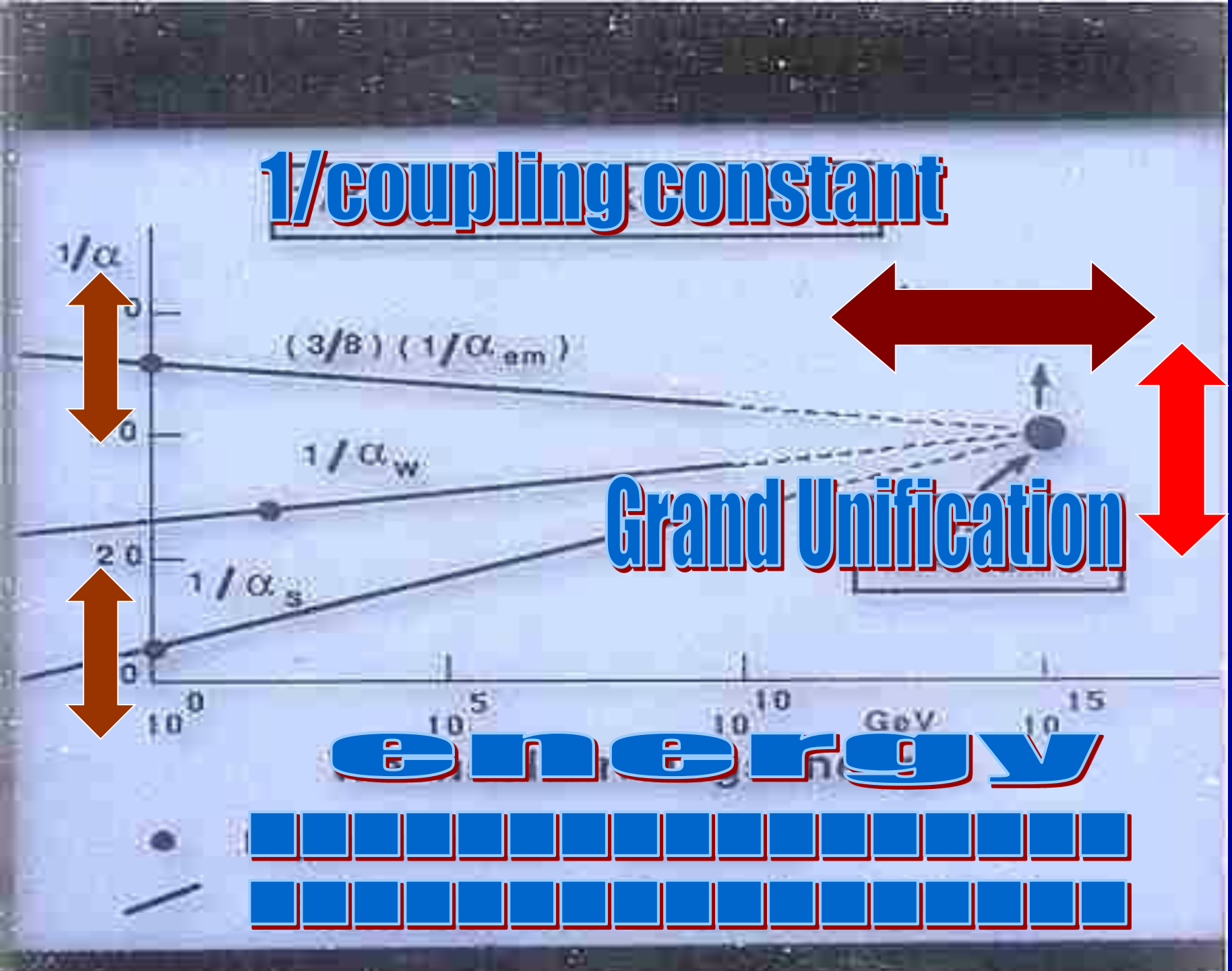
unification coupling constant
unification scale

PARTIAL CANCELLATION? (SUPERSTRINGS)

E. Witten

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

cancellation


1/coupling constant
1/α
(3/8) (1/α em)
1/α w
1/α s
Grand Unification
10^0
10^5
10^10
GeV
10^15
energy

MPQ: new experiment

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


Reinhold et al., 2006
VLT Chile

Reinhold et al. PRL 96 (2006)

2 quasars - 12 billion years ➔

$$\rho = \frac{m_p}{m_e}$$

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

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

same sign
as MPQ result

THE MASSES OF ATOMIC NUCLEI DEPEND ON TIME!

energy not strictly conserved

Conclusions

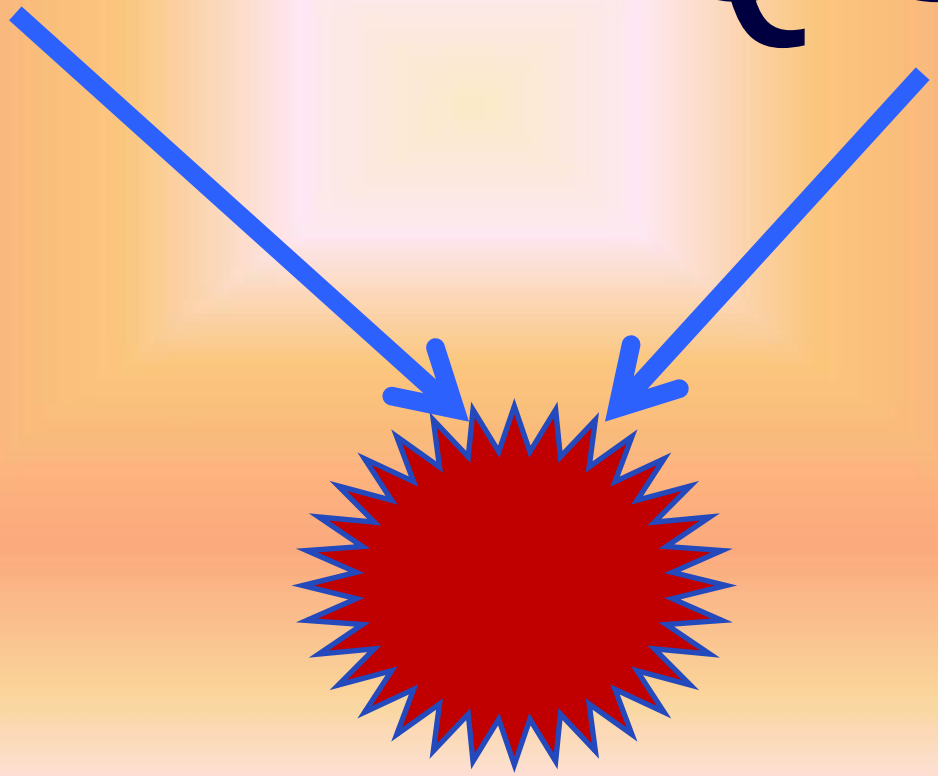
28 constants

24 constants

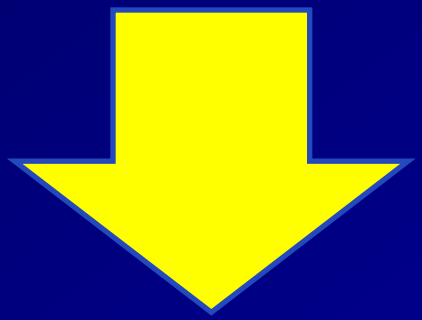
➔ mass parameters

GRAND UNIFICATION

QFD QCD



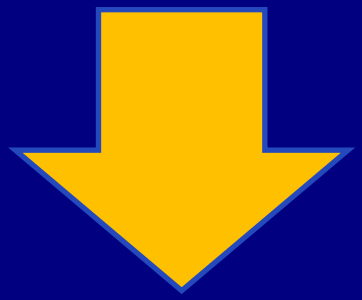
TIME VARIATION ALPHA



TIME VARIATION QCD SCALE

$$\frac{\Delta\Lambda}{\Lambda} \approx 3 \cdot 10^{-15} \; / \; year$$

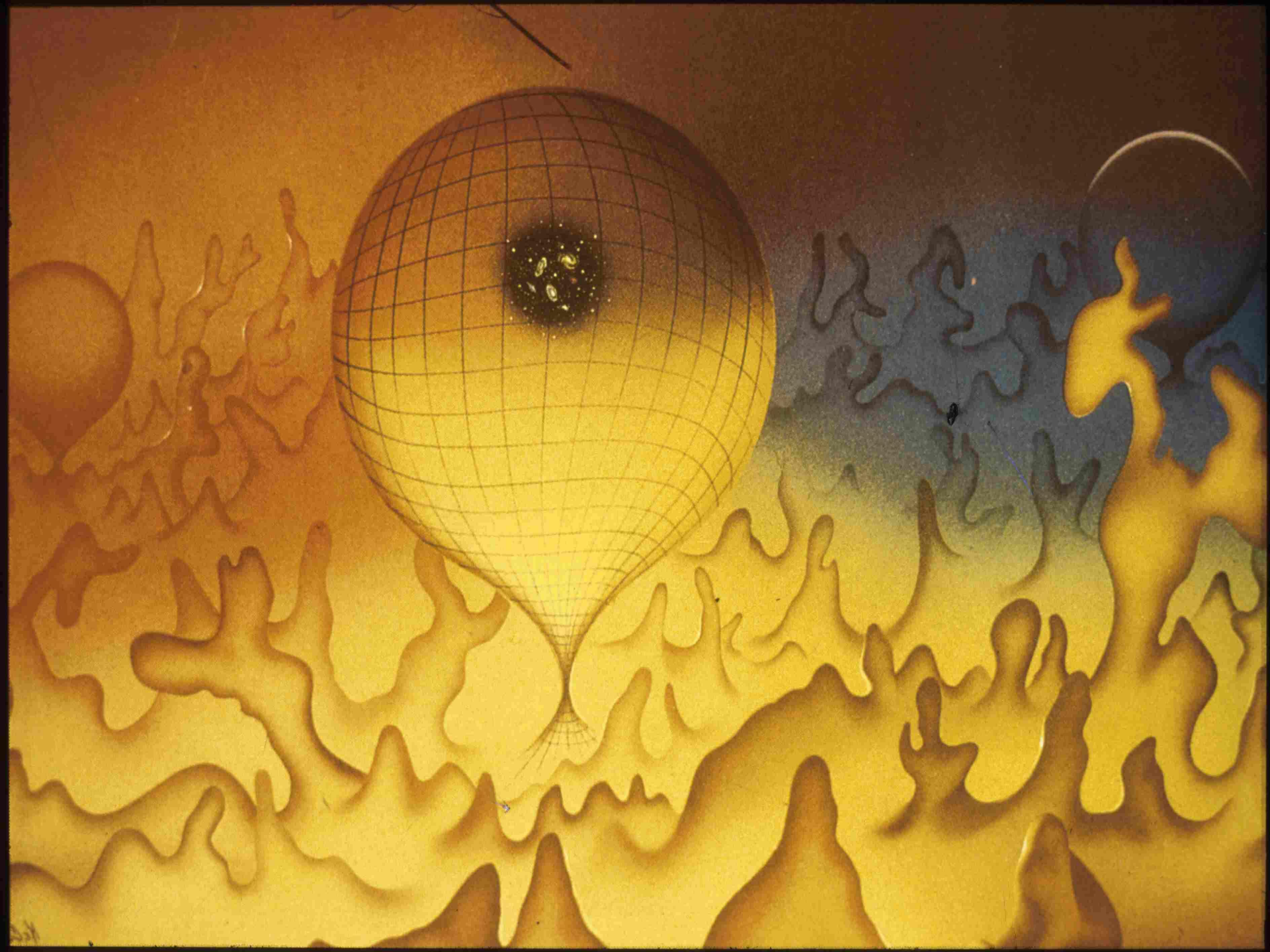
fundamental „constants“

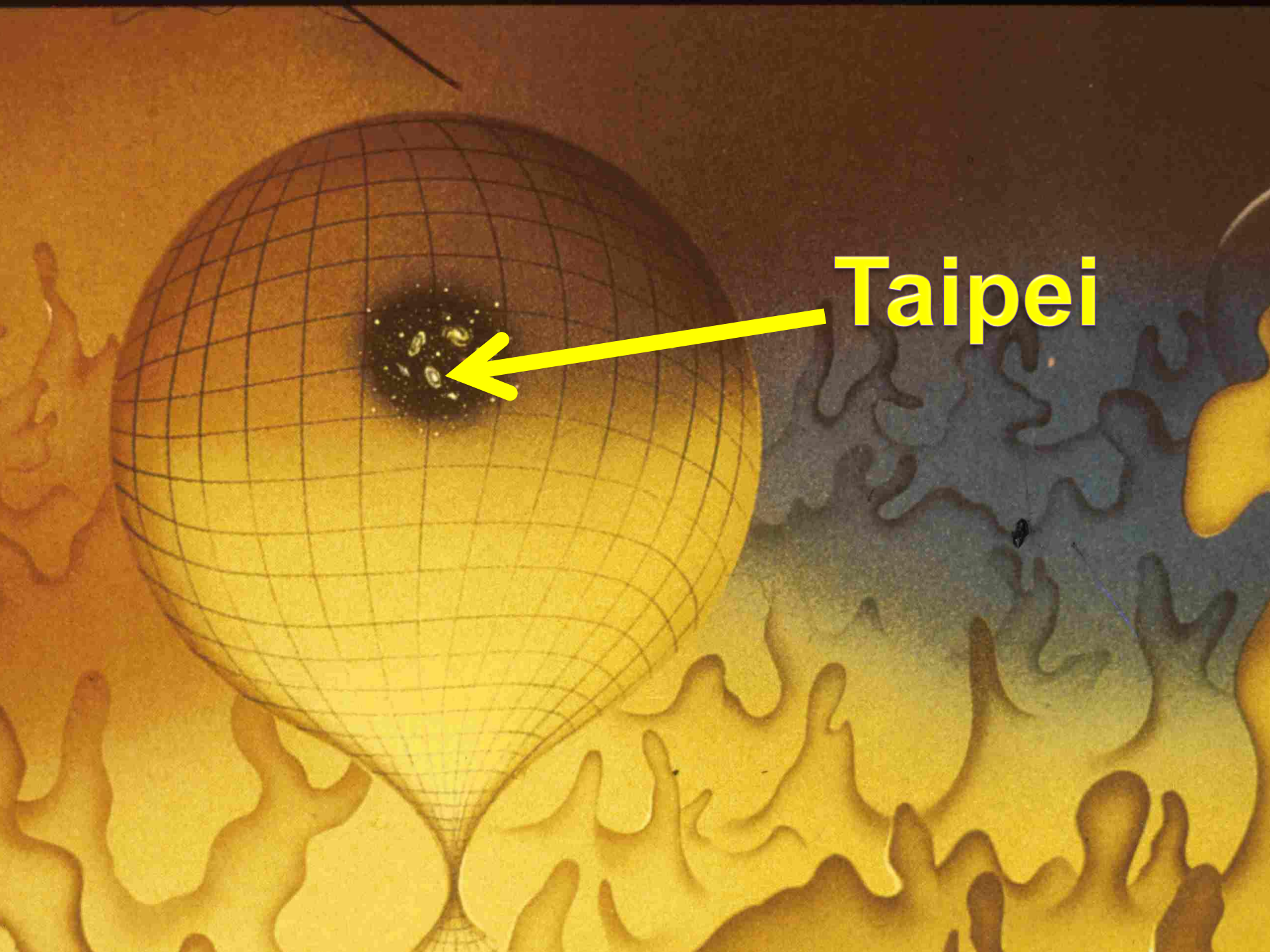


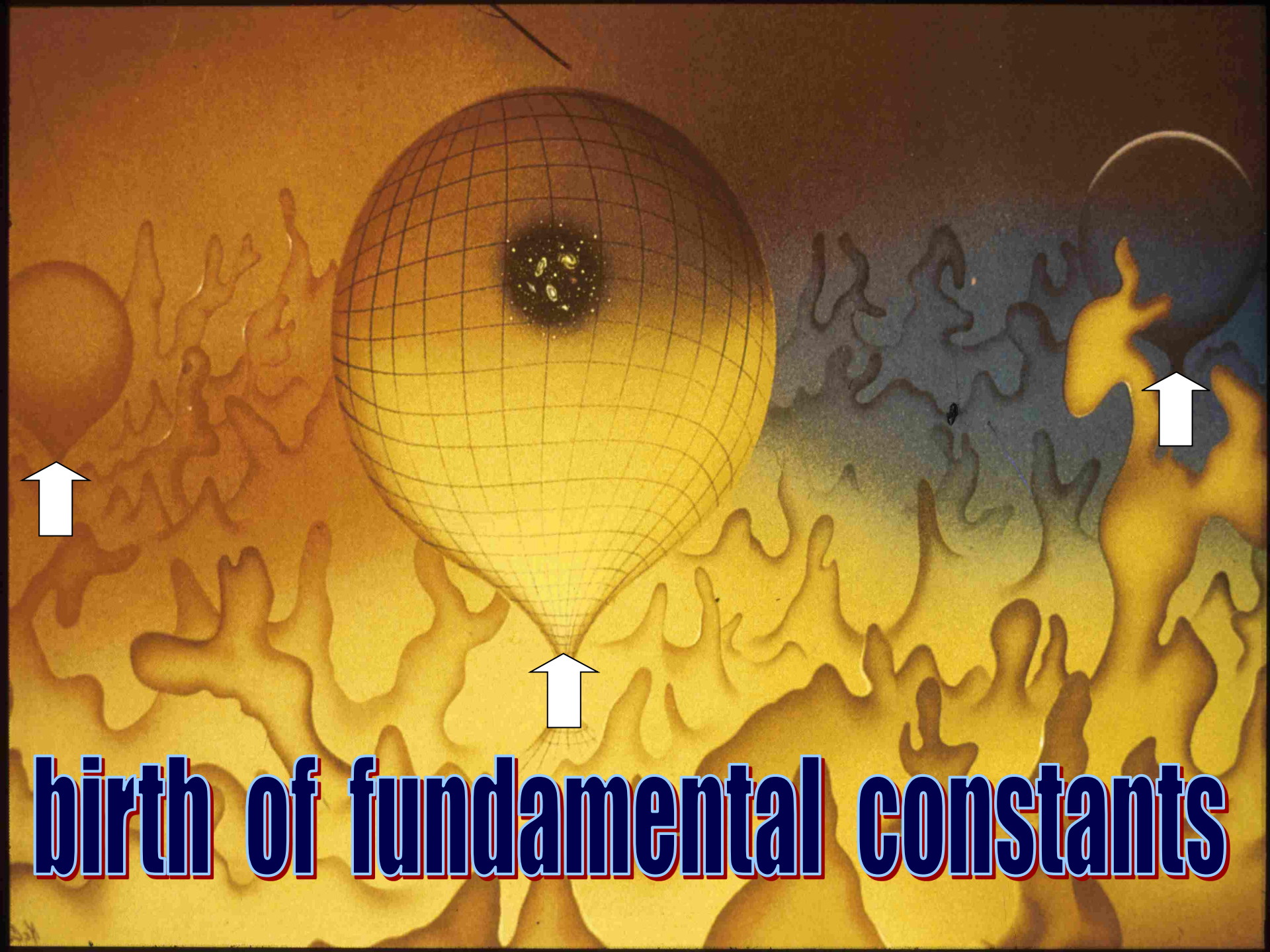
functions of time?

===> cosmology


Universe
⇒ Multiverse

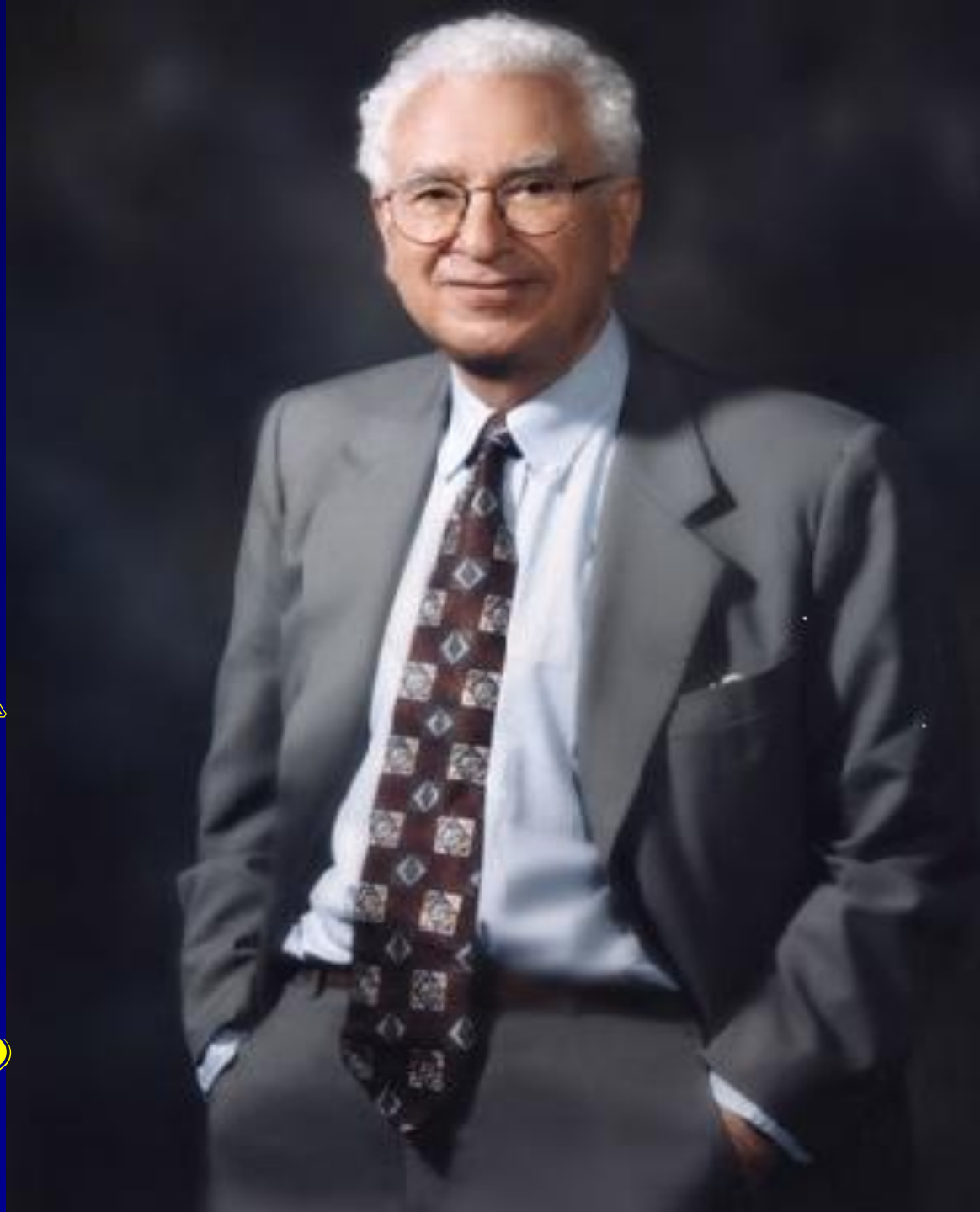


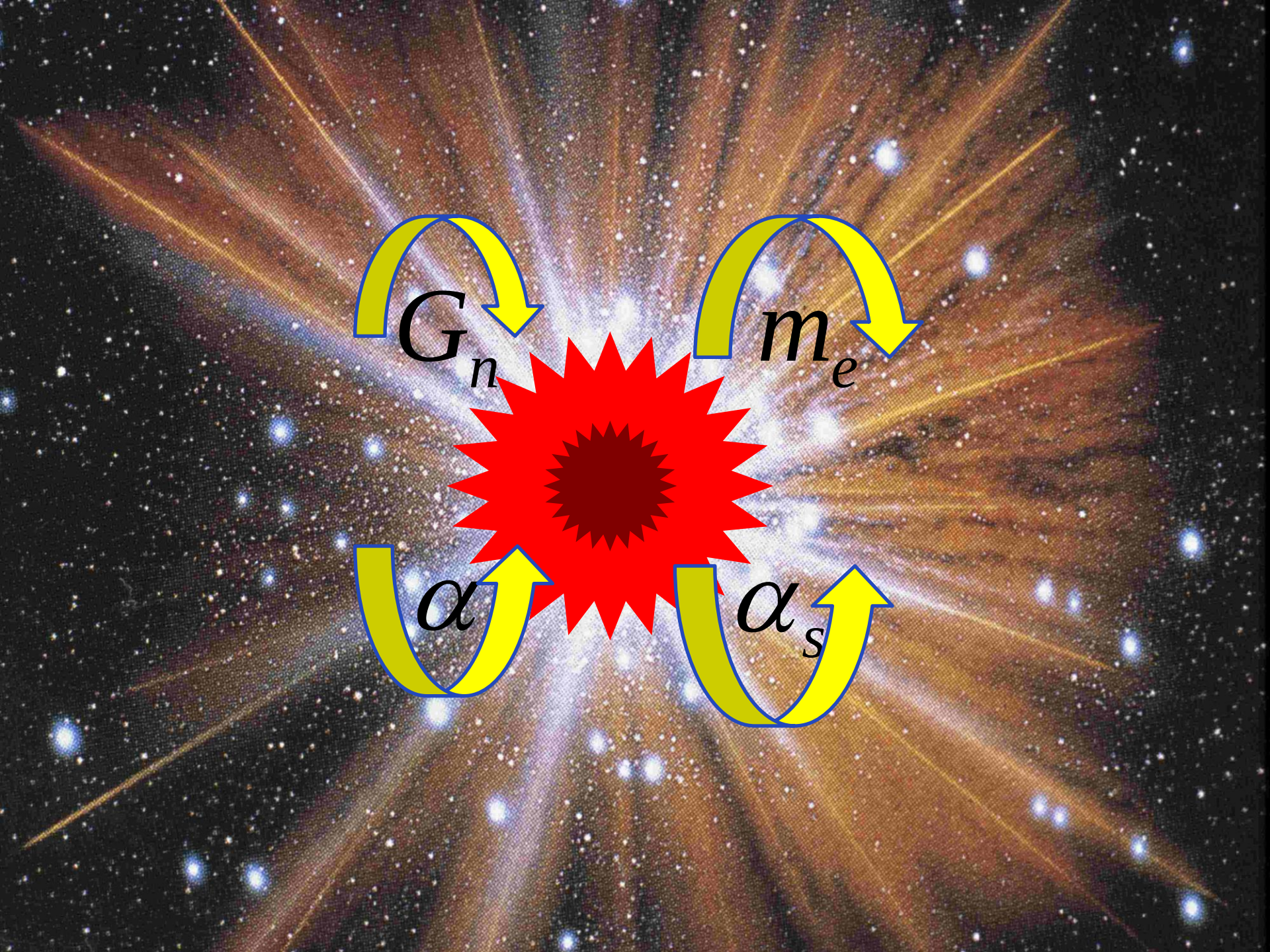

Taipei


birth of fundamental constants

MURRAY GELL-MANN

FUNDAMENTAL CONSTANTS COSMIC ACCIDENTS ?




G_n
m_e
α
α_s


cosmic accidents