Wonder and Charm

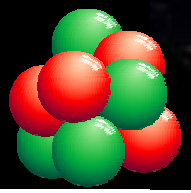
in the

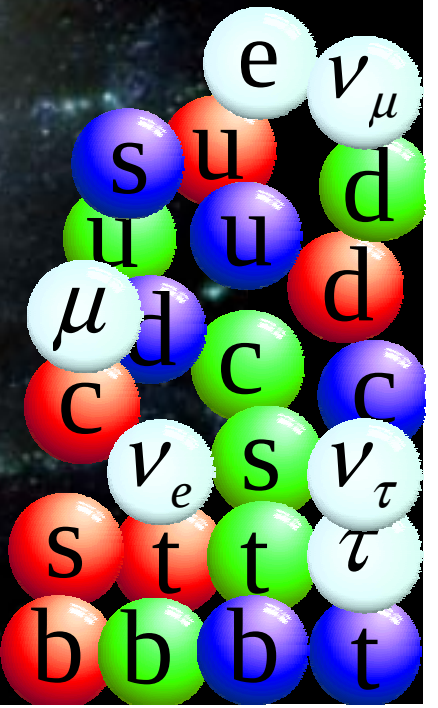
Subatomic Universe

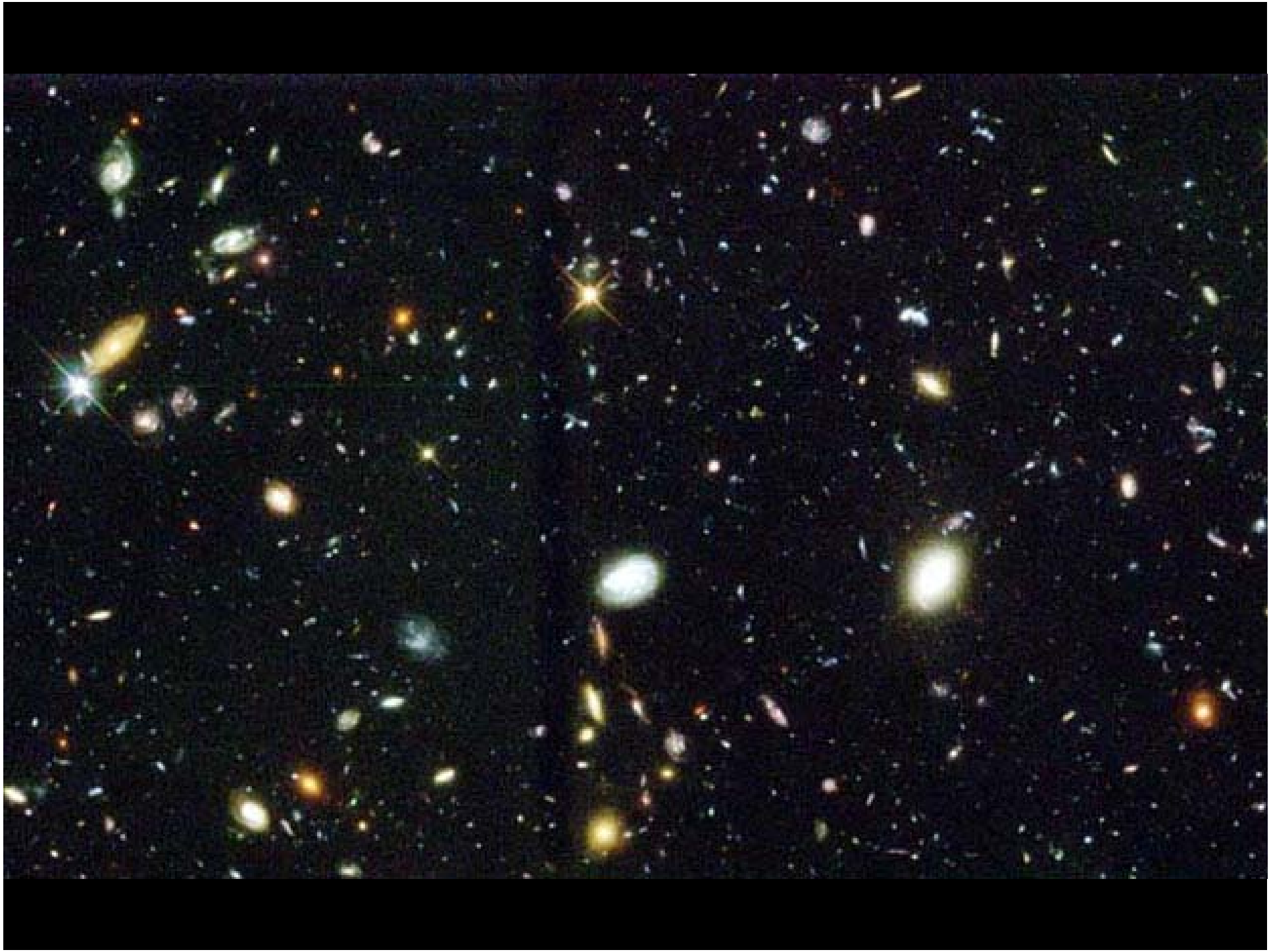
Gerard 't Hooft

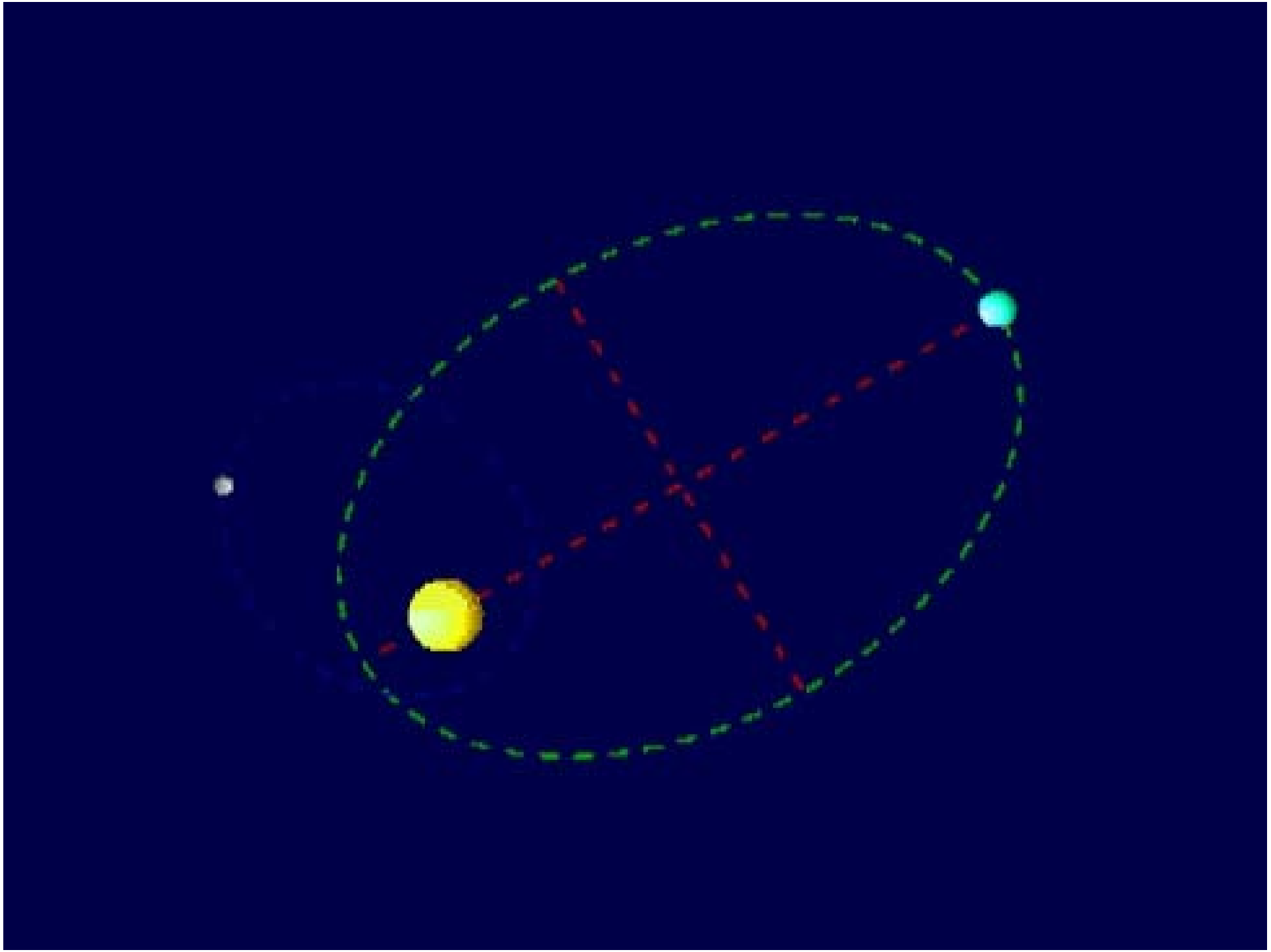
Osaka

October 2, 2002

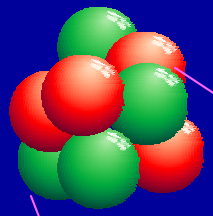








Atomic Nucleus

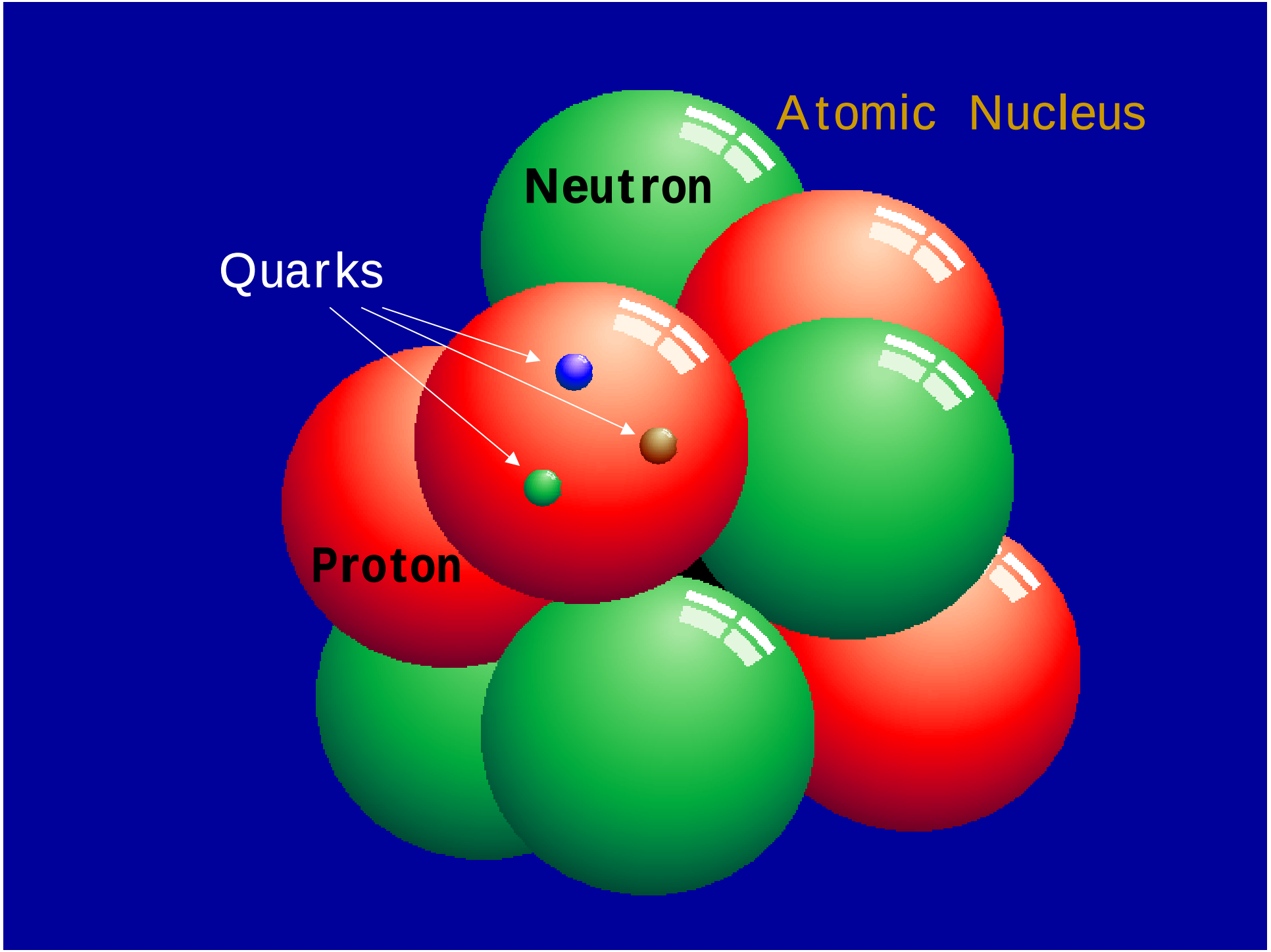


1 Angstrom = $\frac{1}{100.000.000.}$ cm

1 Fermi = $\frac{1}{100.000}$ Angstrom

= $\frac{1}{10.000.000.000.000}$ cm

electron


Atomic Nucleus
Neutron
Quarks
Proton

1969

photon γ

spin $= 1$

Leptons

e^- ν_e

μ^- ν_μ

spin $= \frac{1}{2}$

anti-leptons

Hadrons

mesons

π^+ π^- π^o

K^+ K^-

K_L K_S

η

spin $= 0$

baryons

P^+ N

Λ

Σ^+ Σ^o Σ^-

Ξ^o Ξ^-

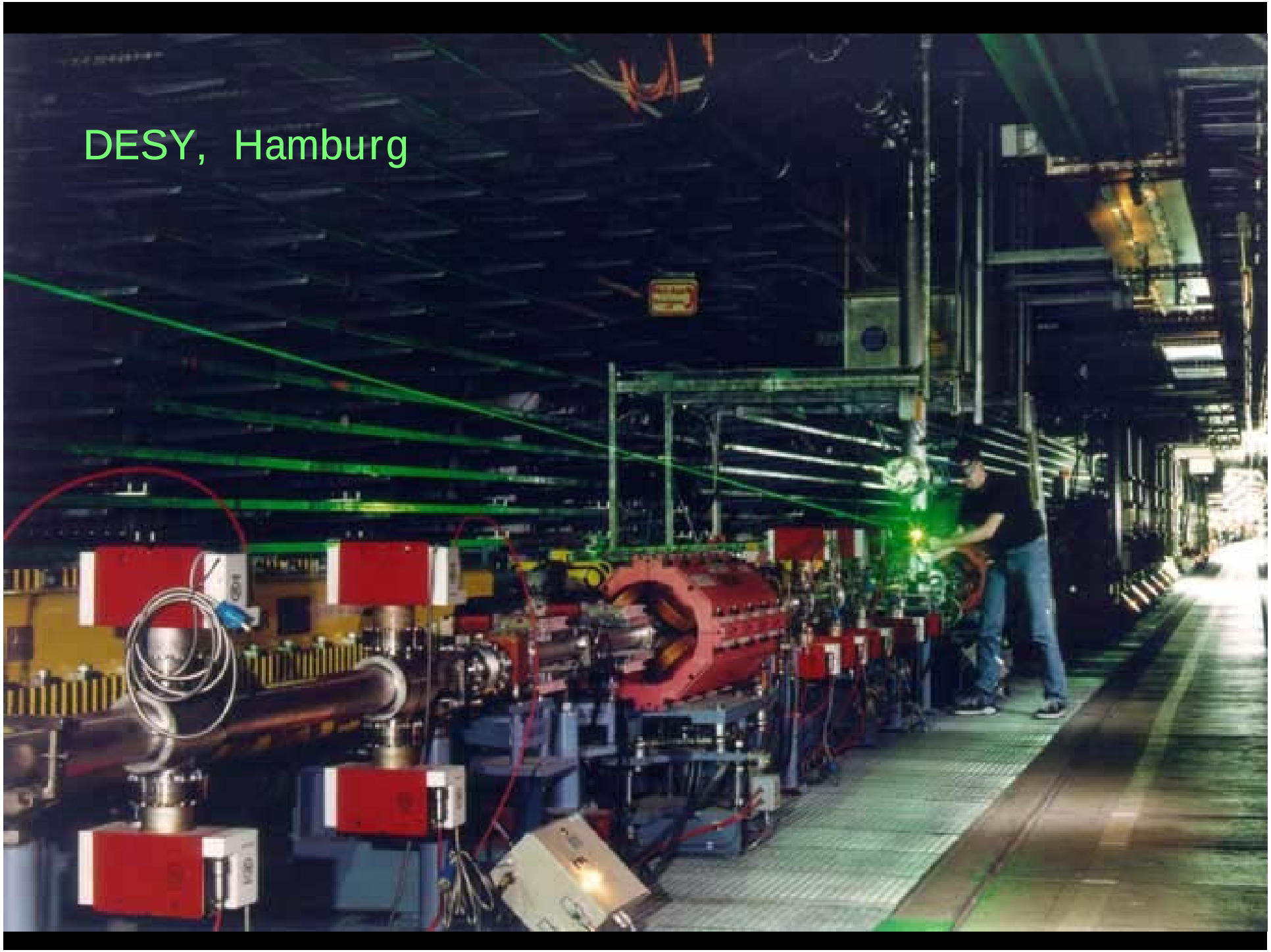
spin $= \frac{1}{2}$

anti-baryons

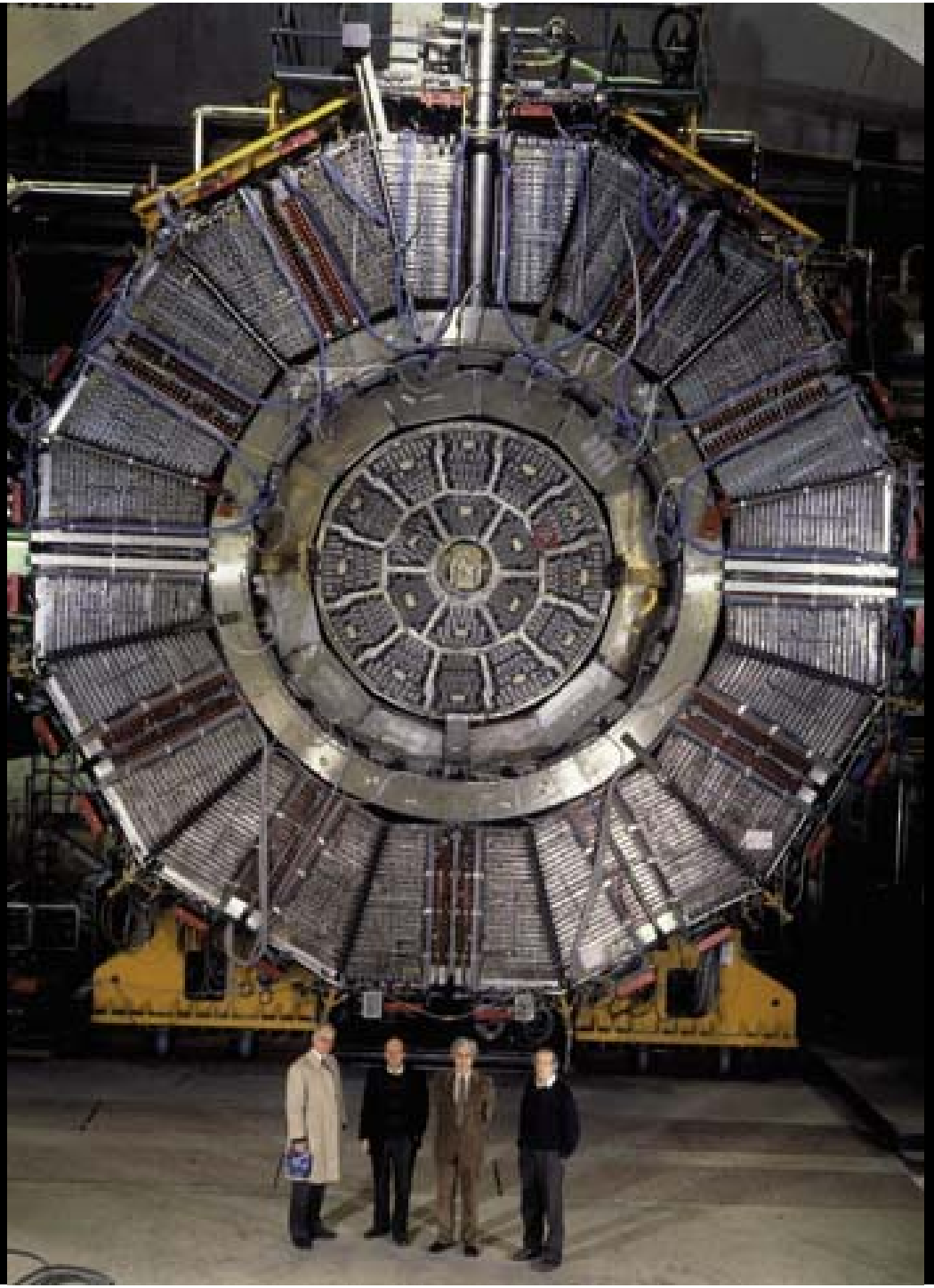
Ω^-

spin $= \frac{3}{2}$

anti-Ω


DESY, Hamburg

Particle detector at CERN



CERN

SpS

&

LHC

(Large Hadron Collider)

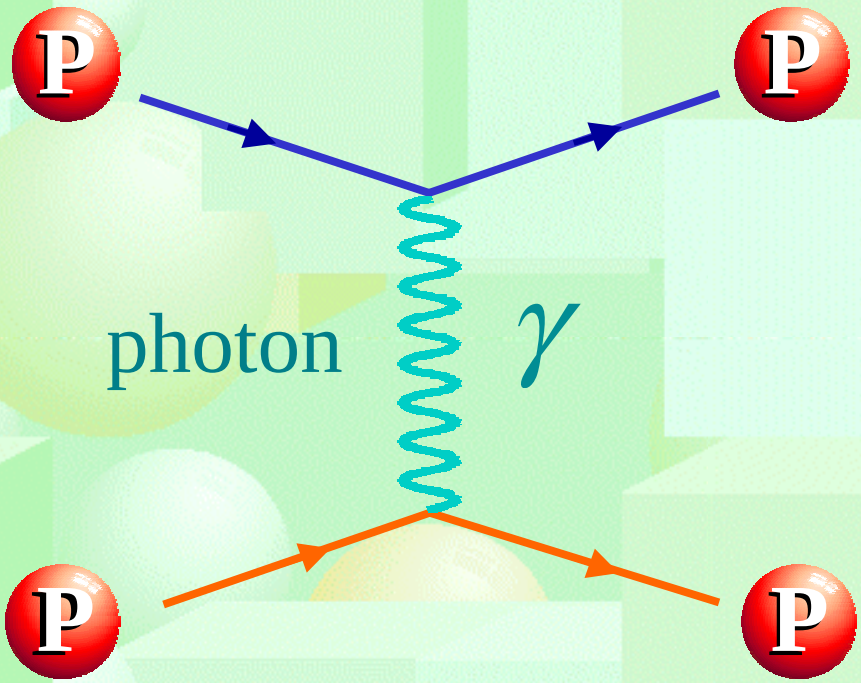
Known from experiment

Forces:

- the ELECTRO MAGNETIC force
- the STRONG force
- the WEAK force

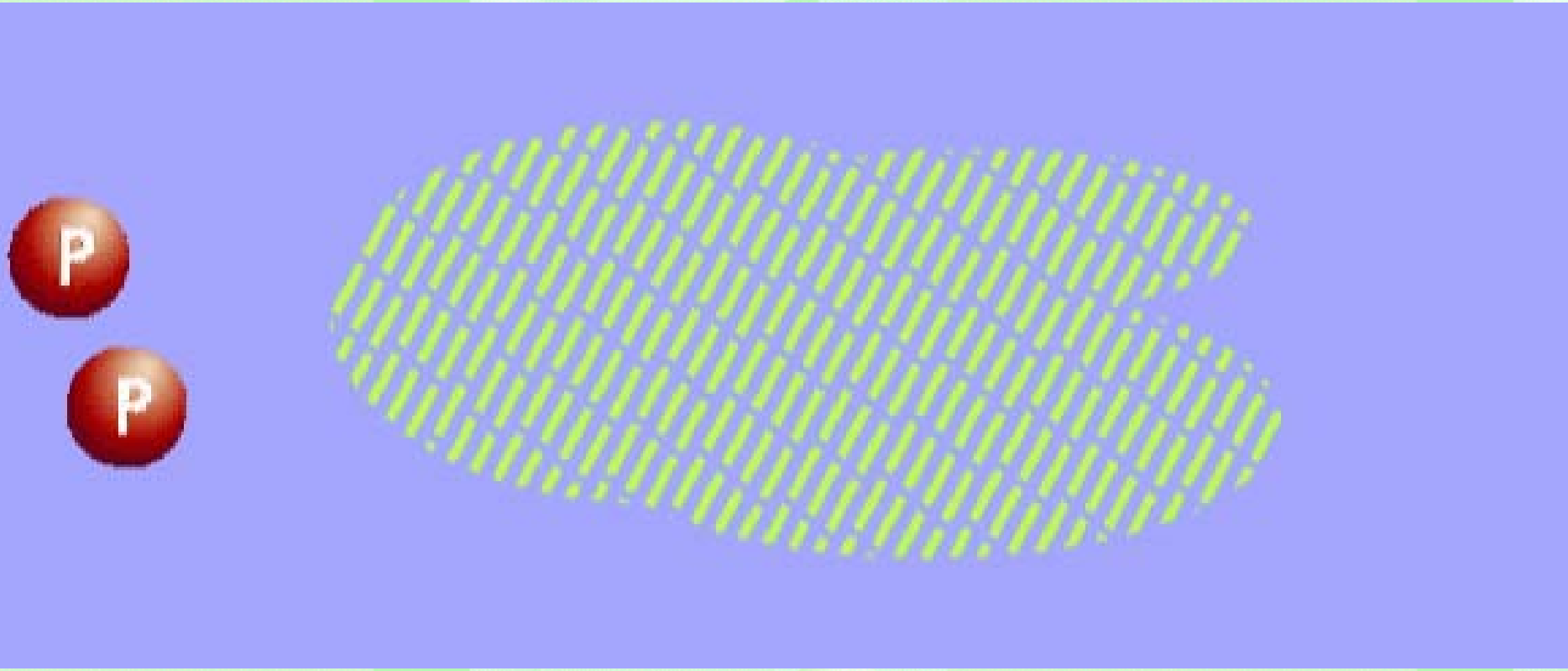
Electro Magnetic Interaction

between electrically charged particles
by photon exchange



The Yang-Mills Field

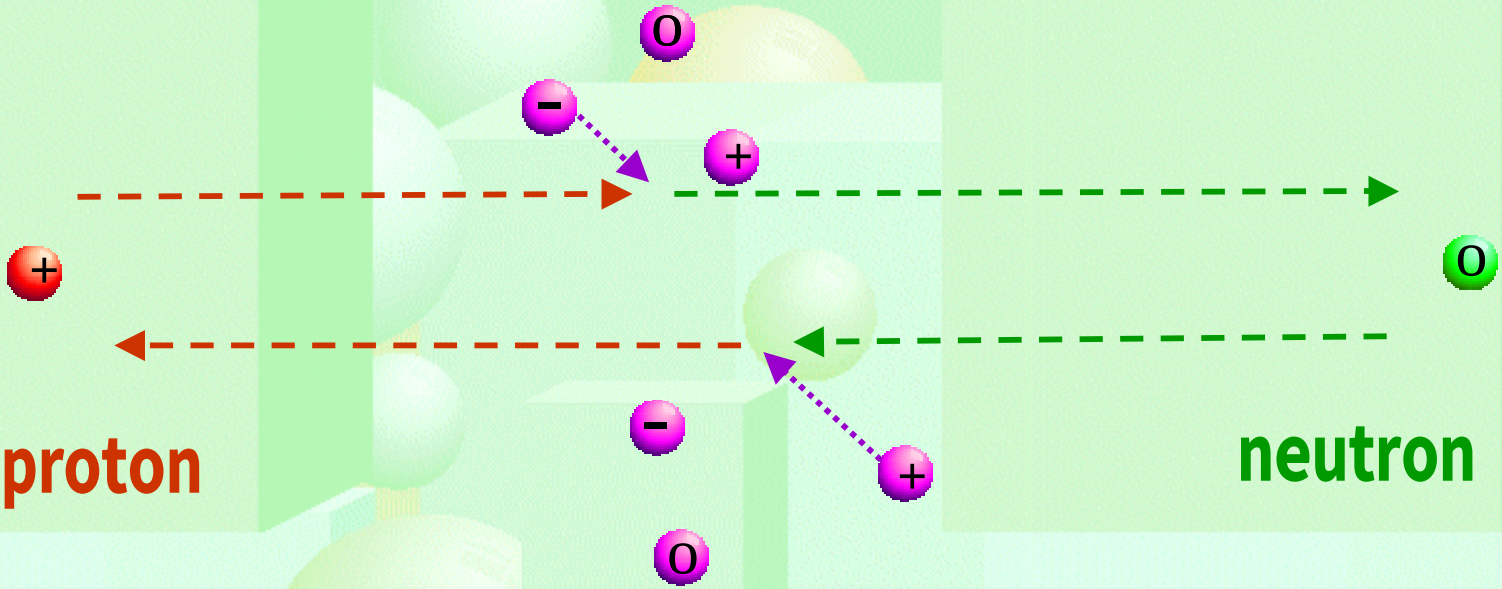
C.N. Yang and R.L. Mills, 1954



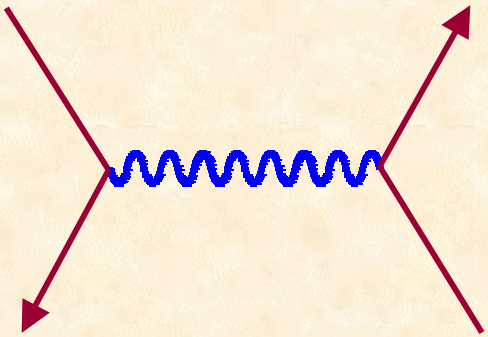
The Yang-Mills Field

C.N. Yang and R.L. Mills, 1954

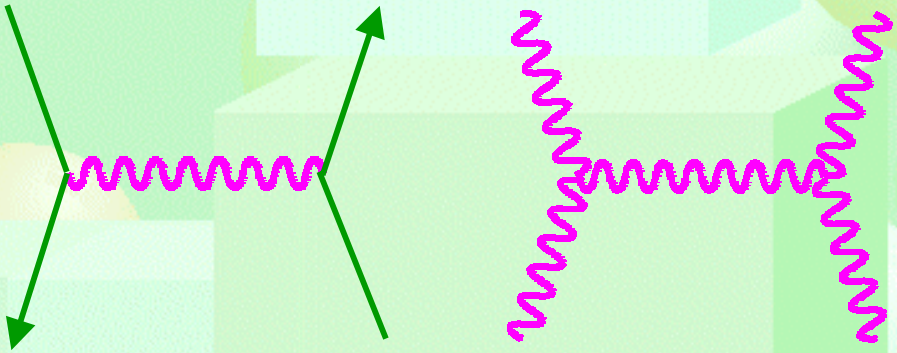
Yang - Mills quanta



Electro-magnetism:



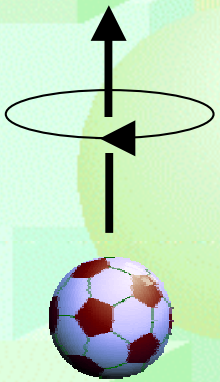
Yang-Mills:



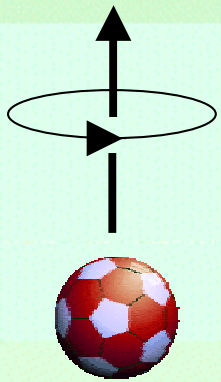
Just as planets and tennis balls,
elementary particles may have ...

Spin !

And, neutrinos only rotate in one direction !



Neutrino



Anti Neutrino

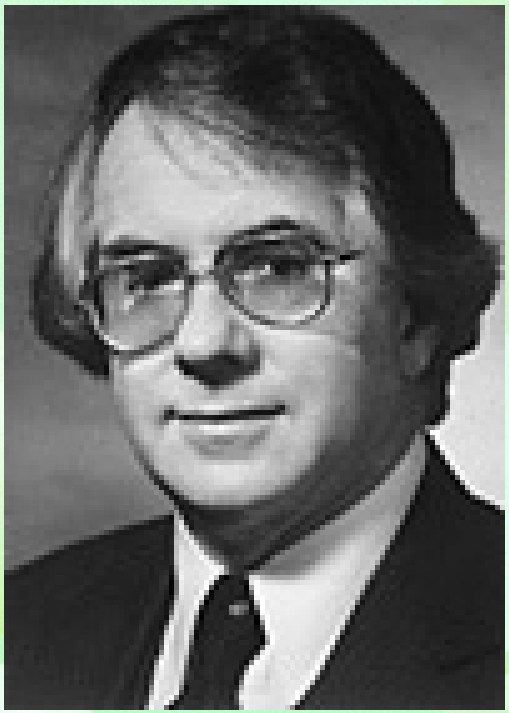
Multiplets

According to the Yang-Mills-theory

$\text{spin} = \frac{1}{2}$	P N	Nucleons
$\text{spin} = 0$	π^+ π^o π^-	pions
$\text{spin} = 1$	A^+ A^o A^-	Yang-Mills bosons

A. Salam

S.L. Glashow



St. Weinberg

Weinberg's lepton model

Leptons

e^- μ^-

spin $= \frac{1}{2}$ RIGHT

ν_e ν_μ

e^- μ^-

spin $= \frac{1}{2}$ LEFT

Gauge bosons

W^+

Z^o

W^-

γ

spin $= 1$

spin $= 0$ H^0

Higgs

Anti-Leptons

e^+ μ^+

spin $= \frac{1}{2}$ LEFT

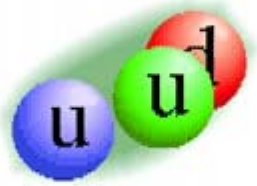
$\bar{\nu}_e$ $\bar{\nu}_\mu$

e^+ μ^+

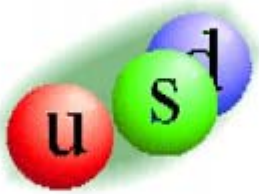
spin $= \frac{1}{2}$ RIGHT

The hadronic particles …

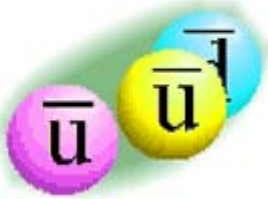
Proton

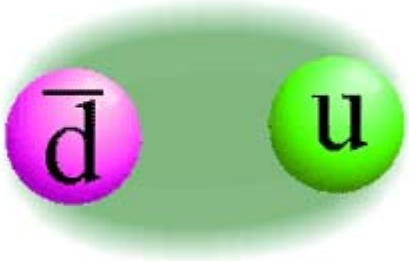


Lambda

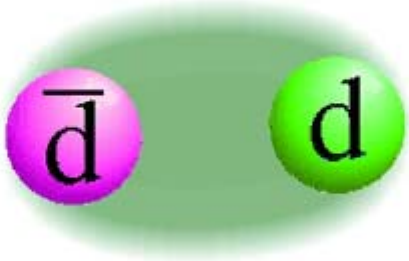


Antiproton



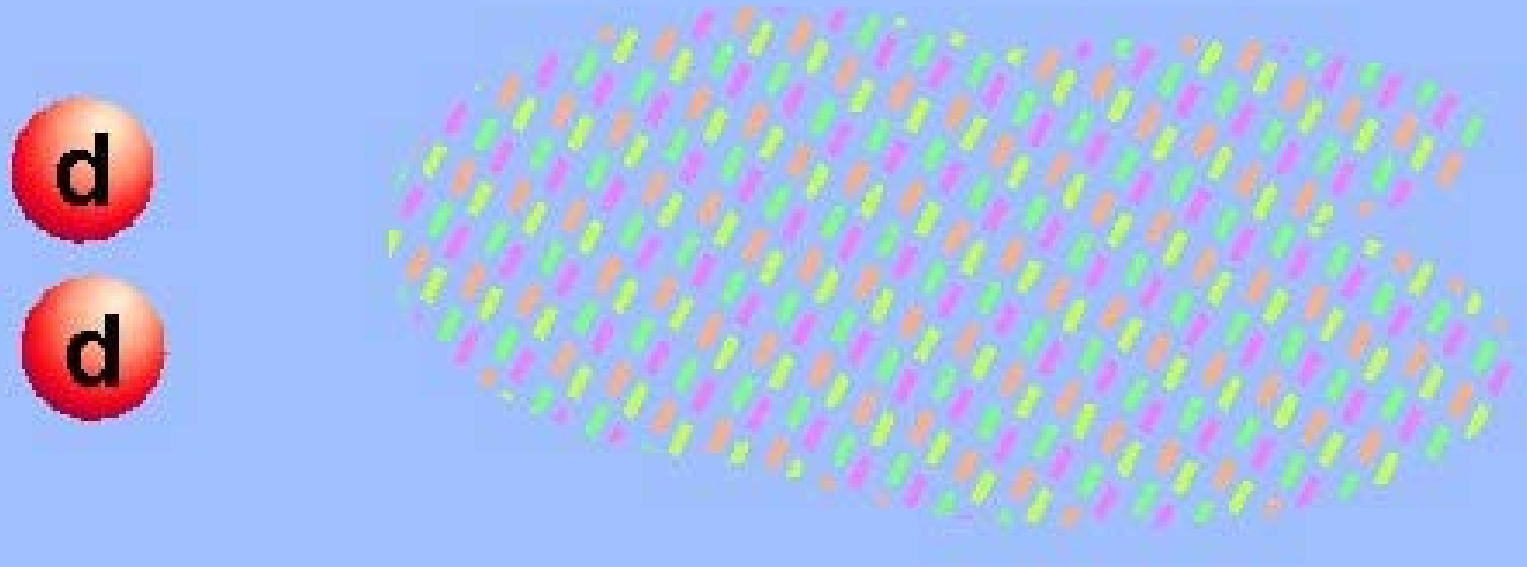


Pi-plus



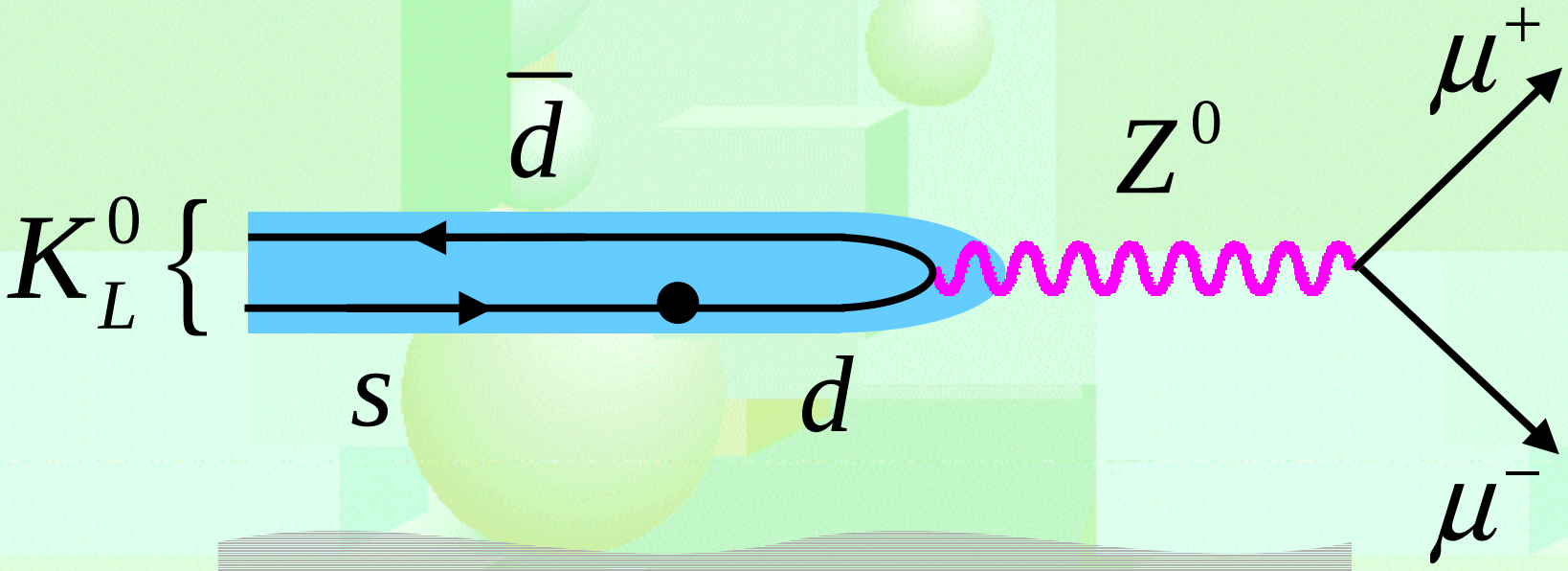
Pi-zero

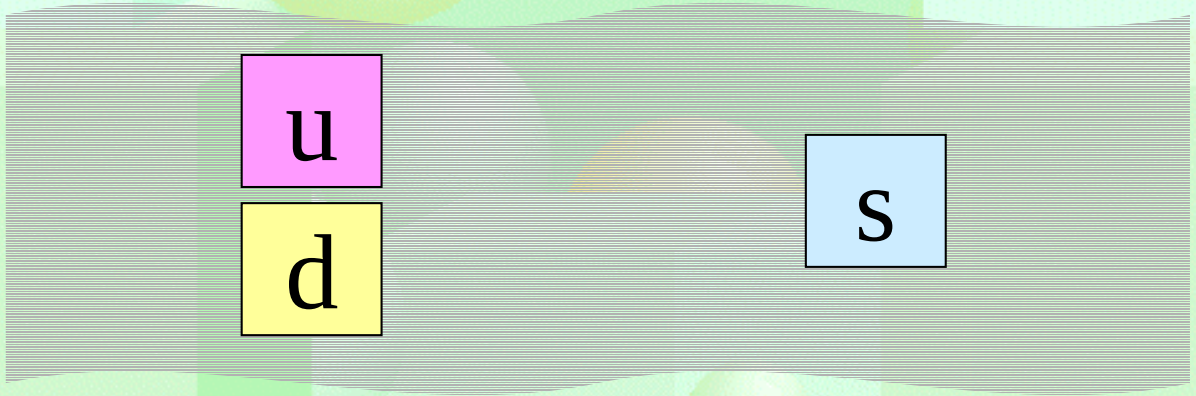
The Yang-Mills Colour Field



Quantum Chromo Dynamics

Flavor changing neutral currents

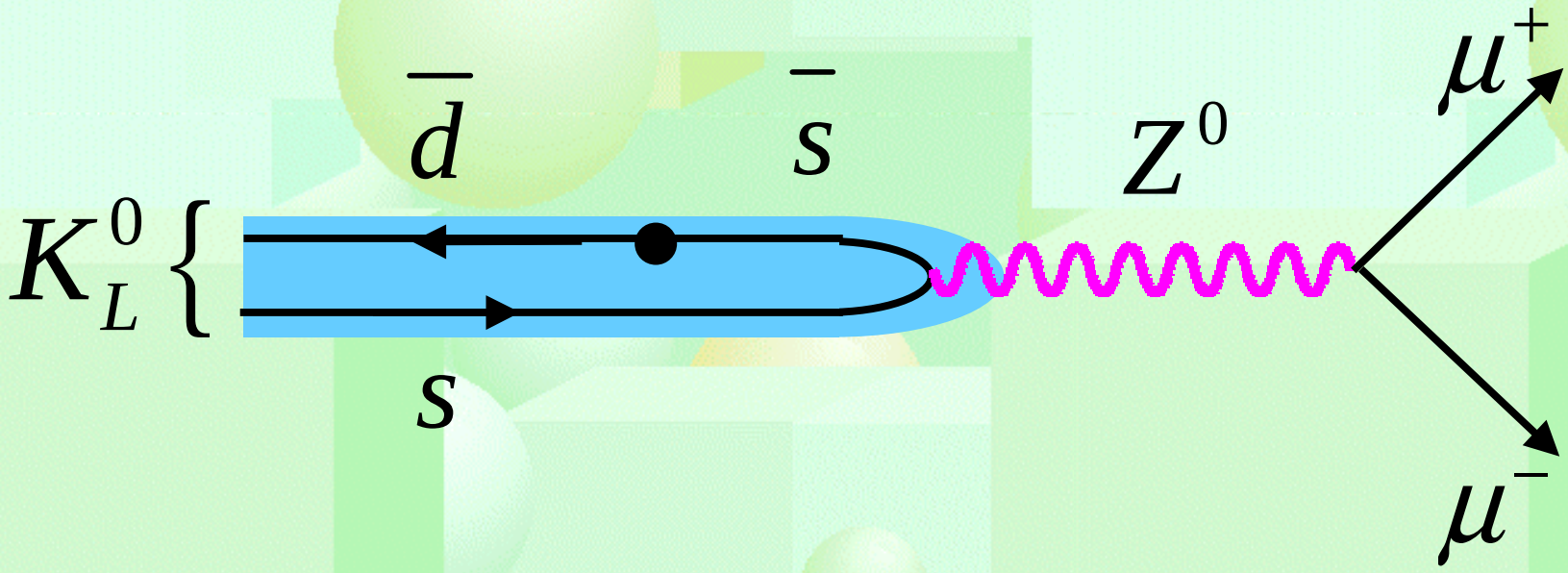




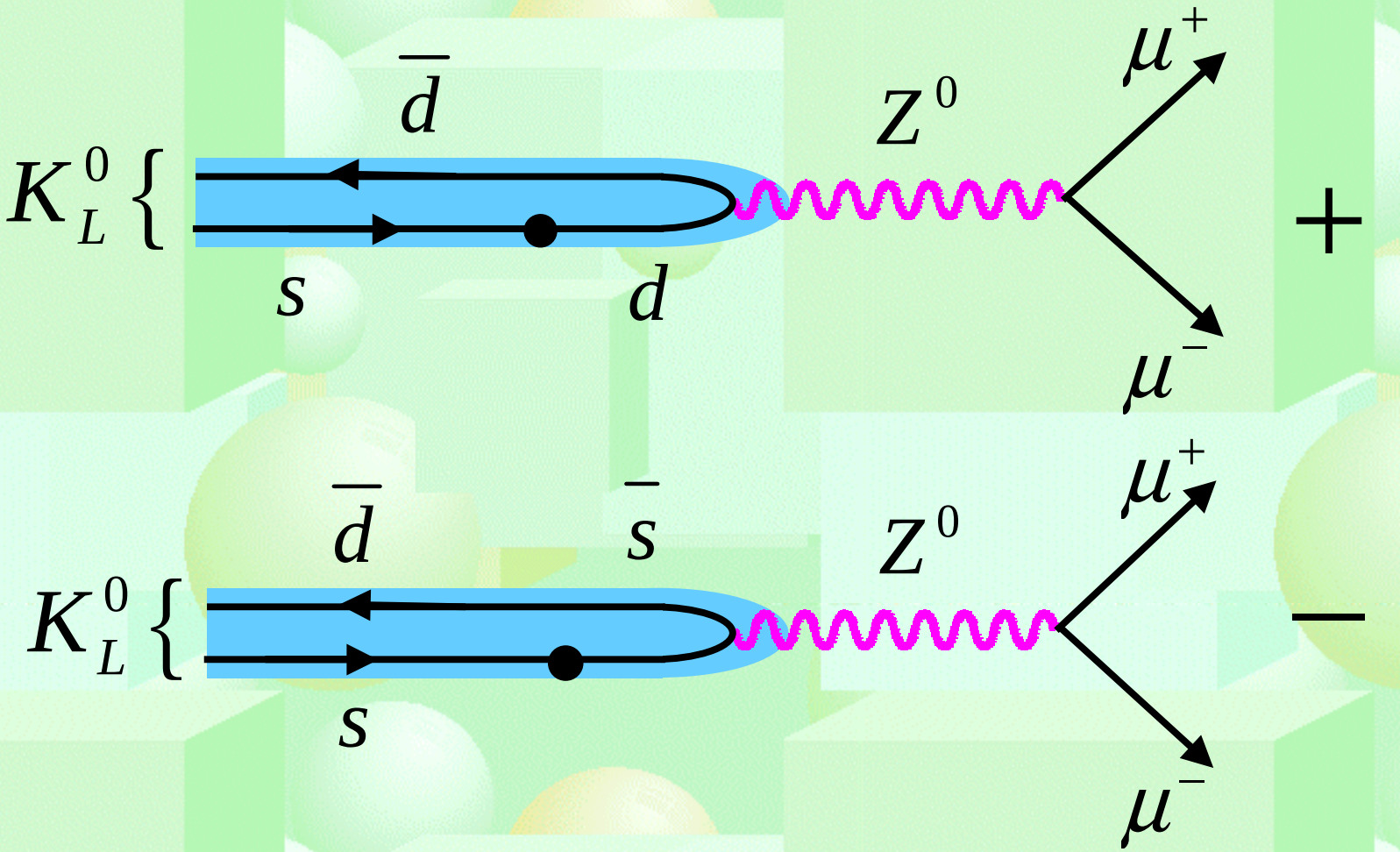
The Charm proposal

(Glashow, Iliopoulos, Majani)

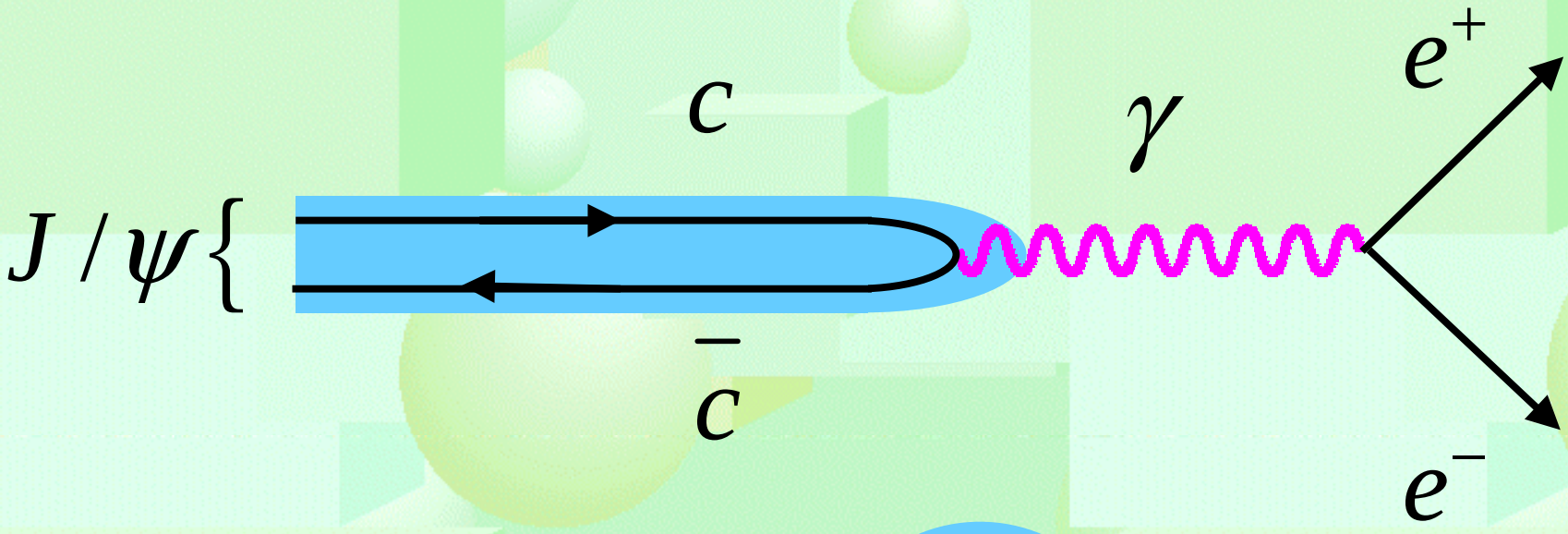
4 MeV	u	c	1500 MeV
8 MeV	d	s	180 MeV

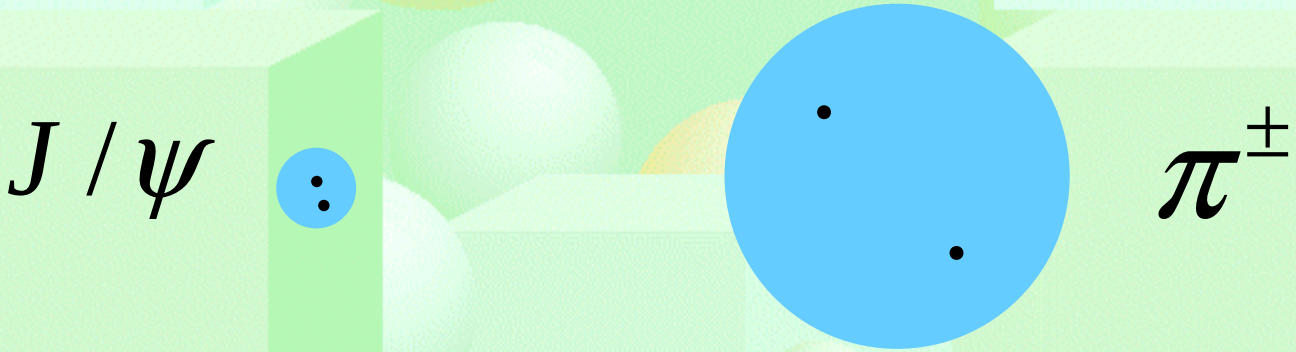


The GIM Mechanism

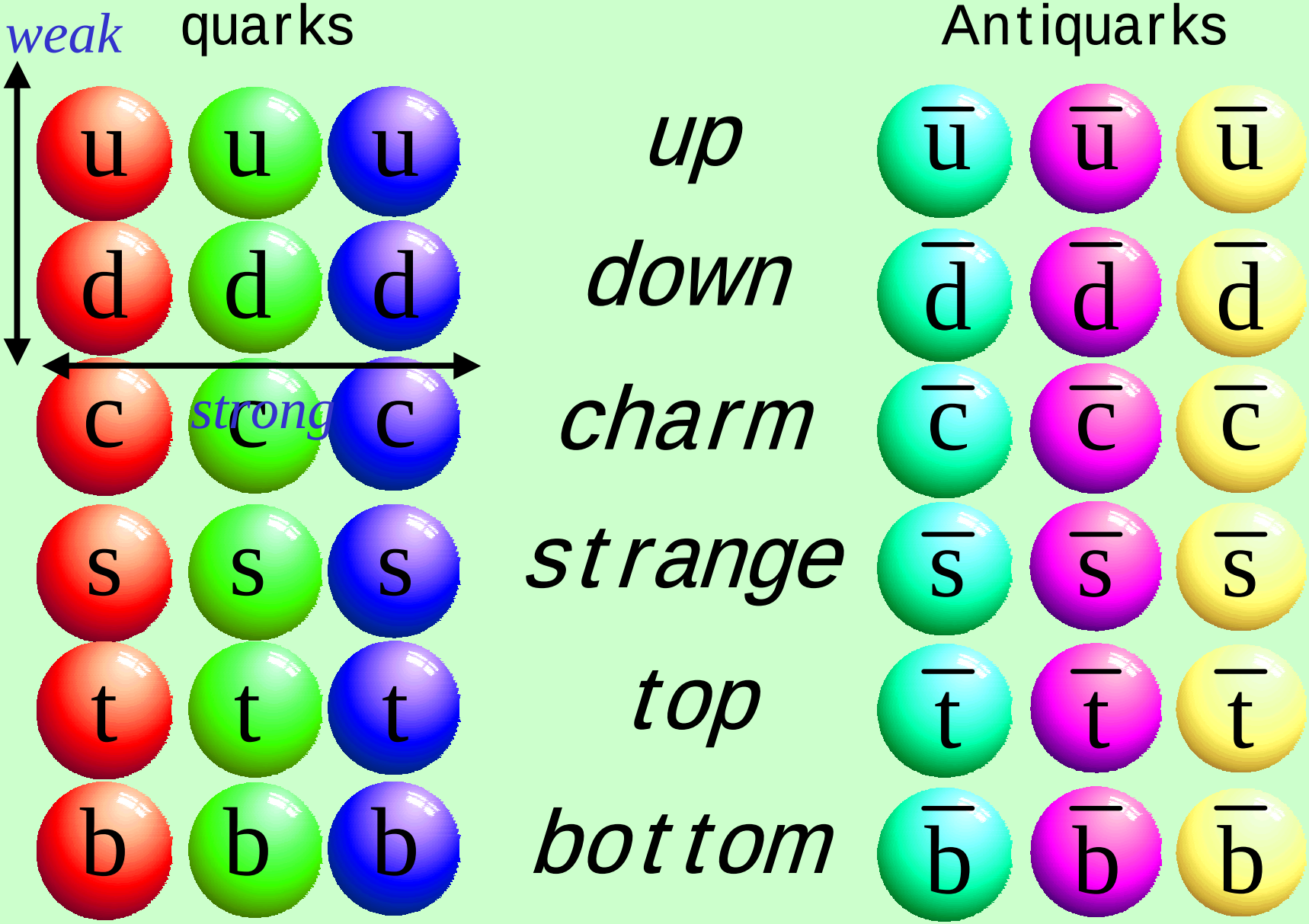


The J/ψ



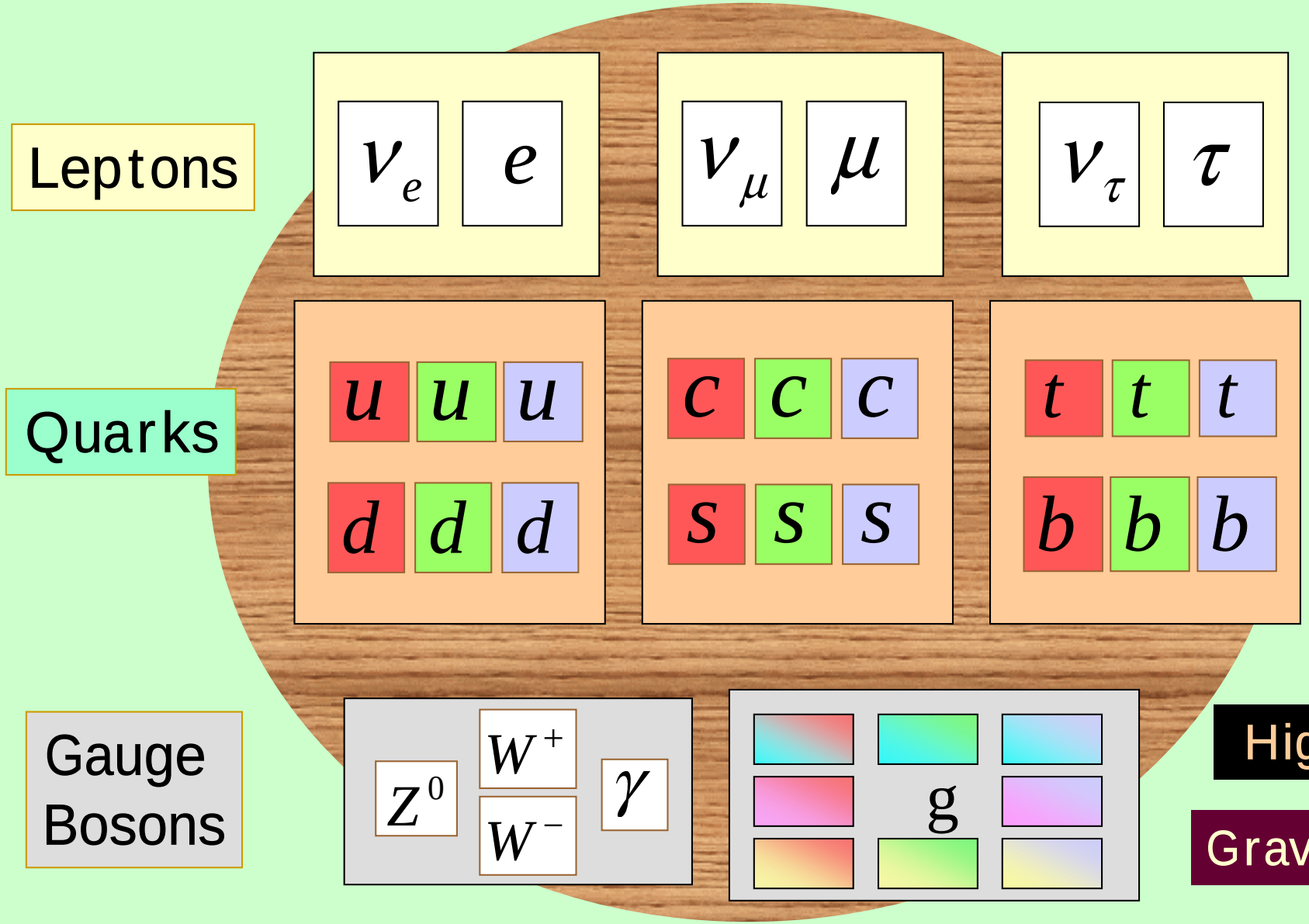


Quark species

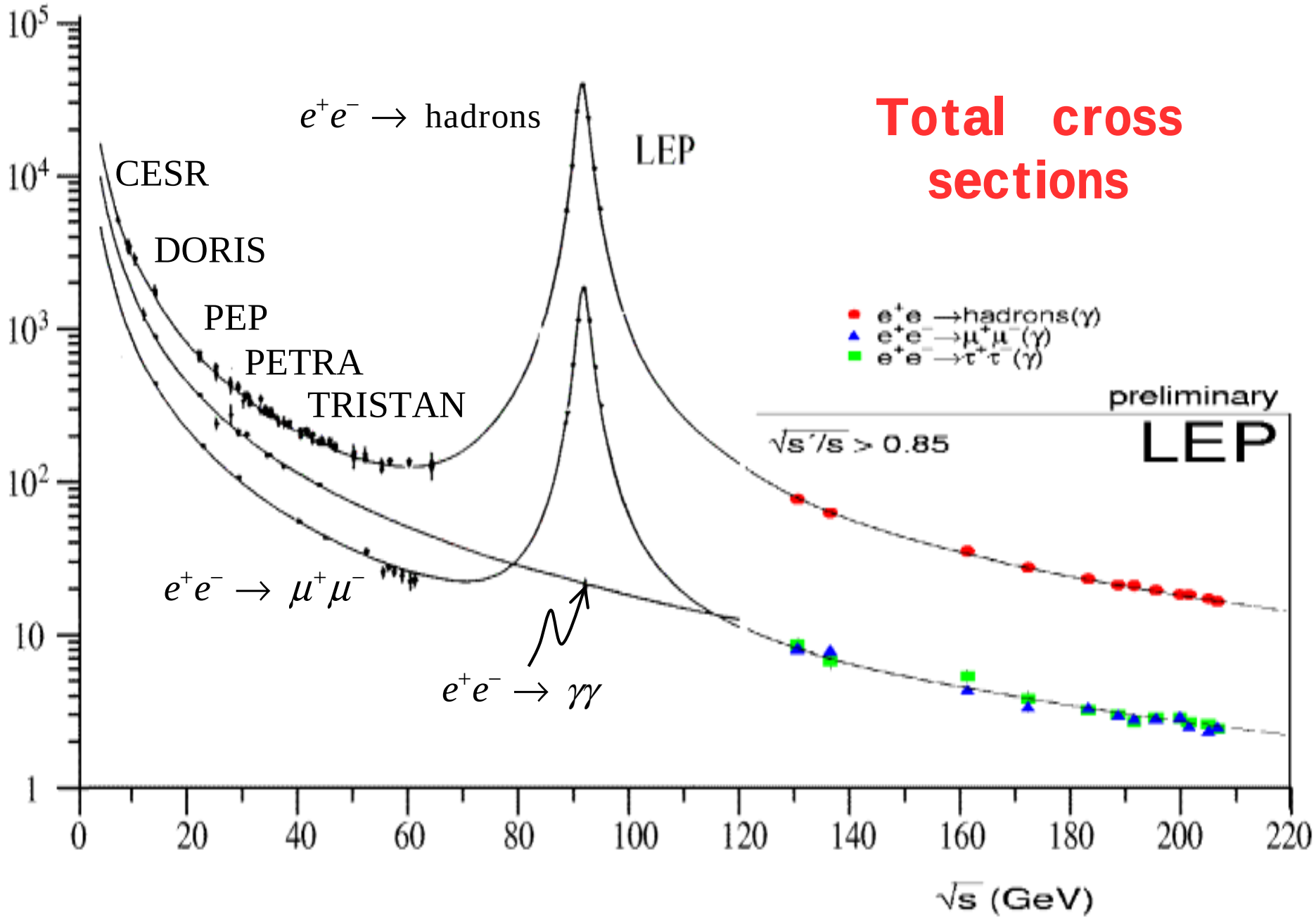


The Standard Model

Generation I Generation II Generation III

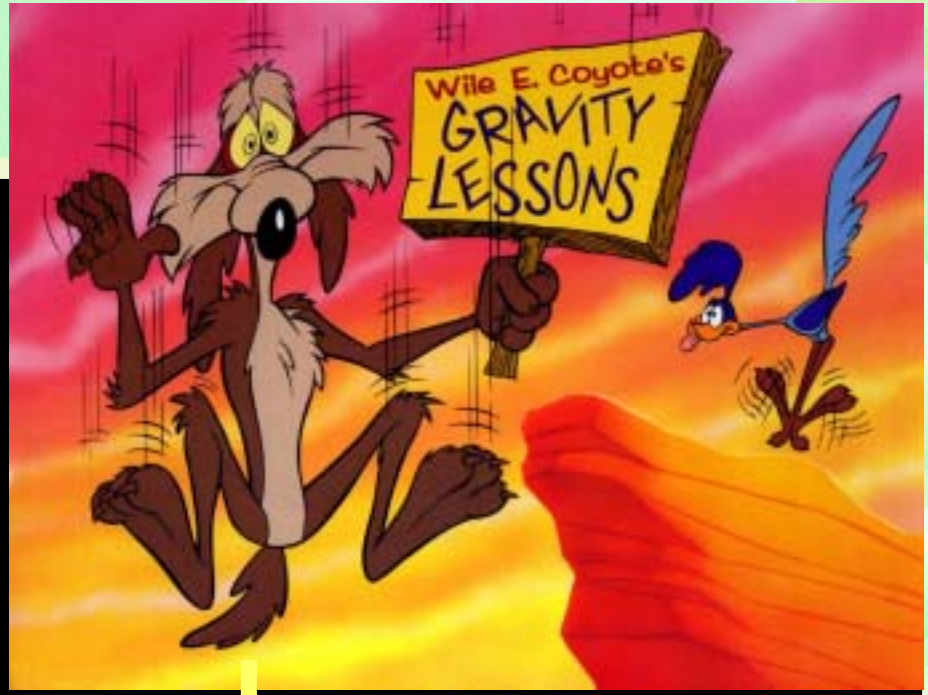


Total cross sections



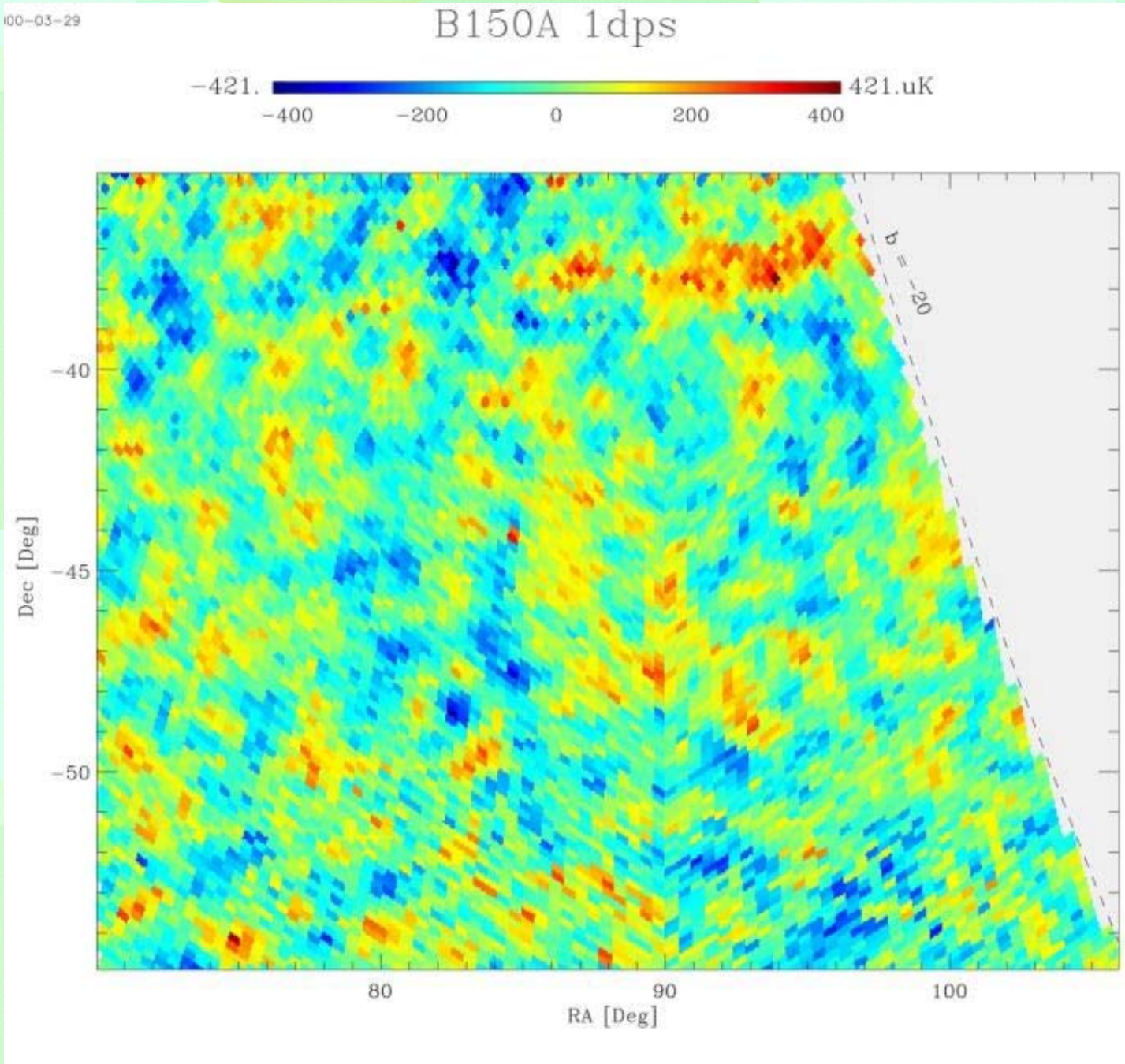
The fourth force:

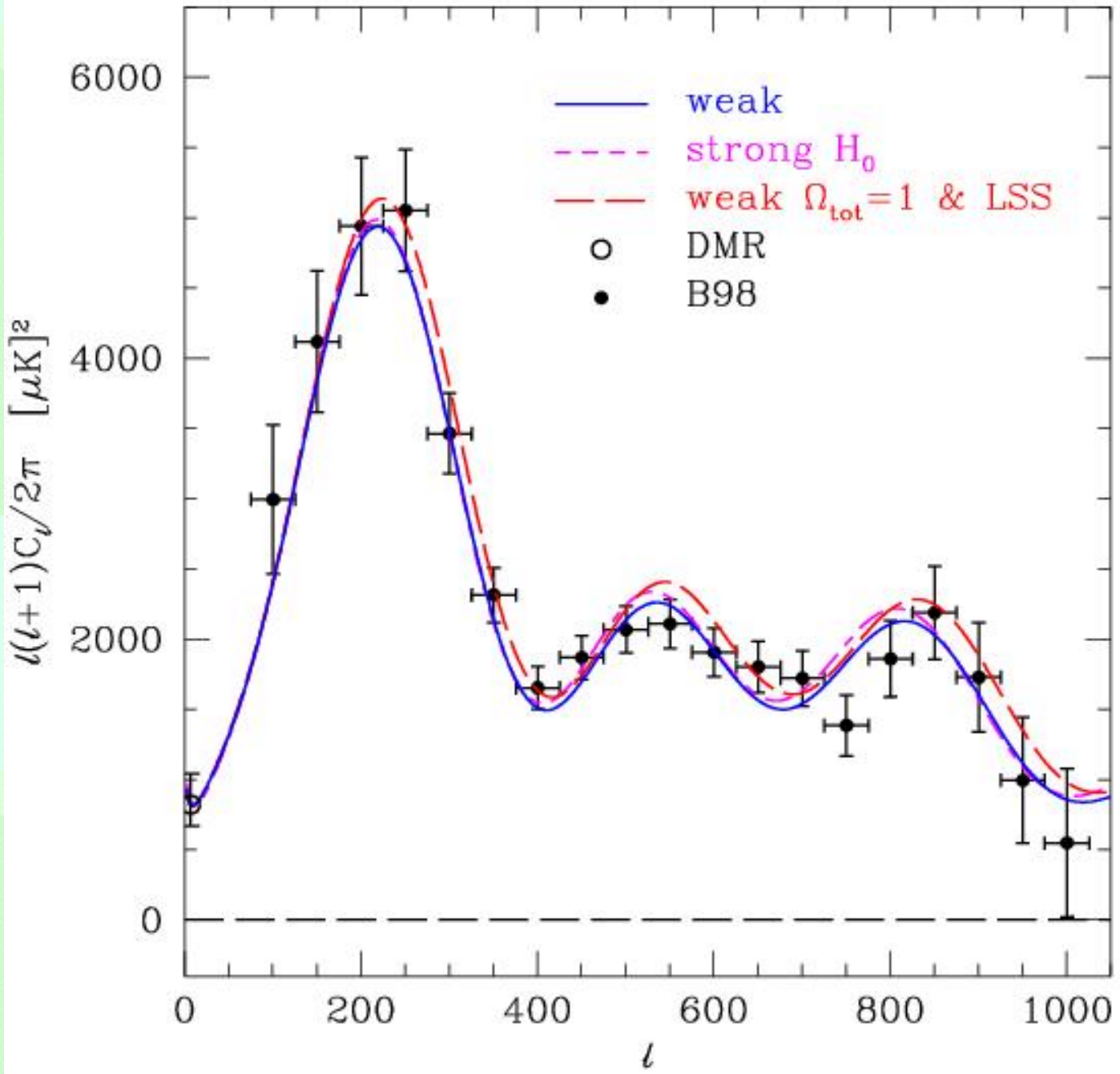
Gravitation



A brief history of the Universe

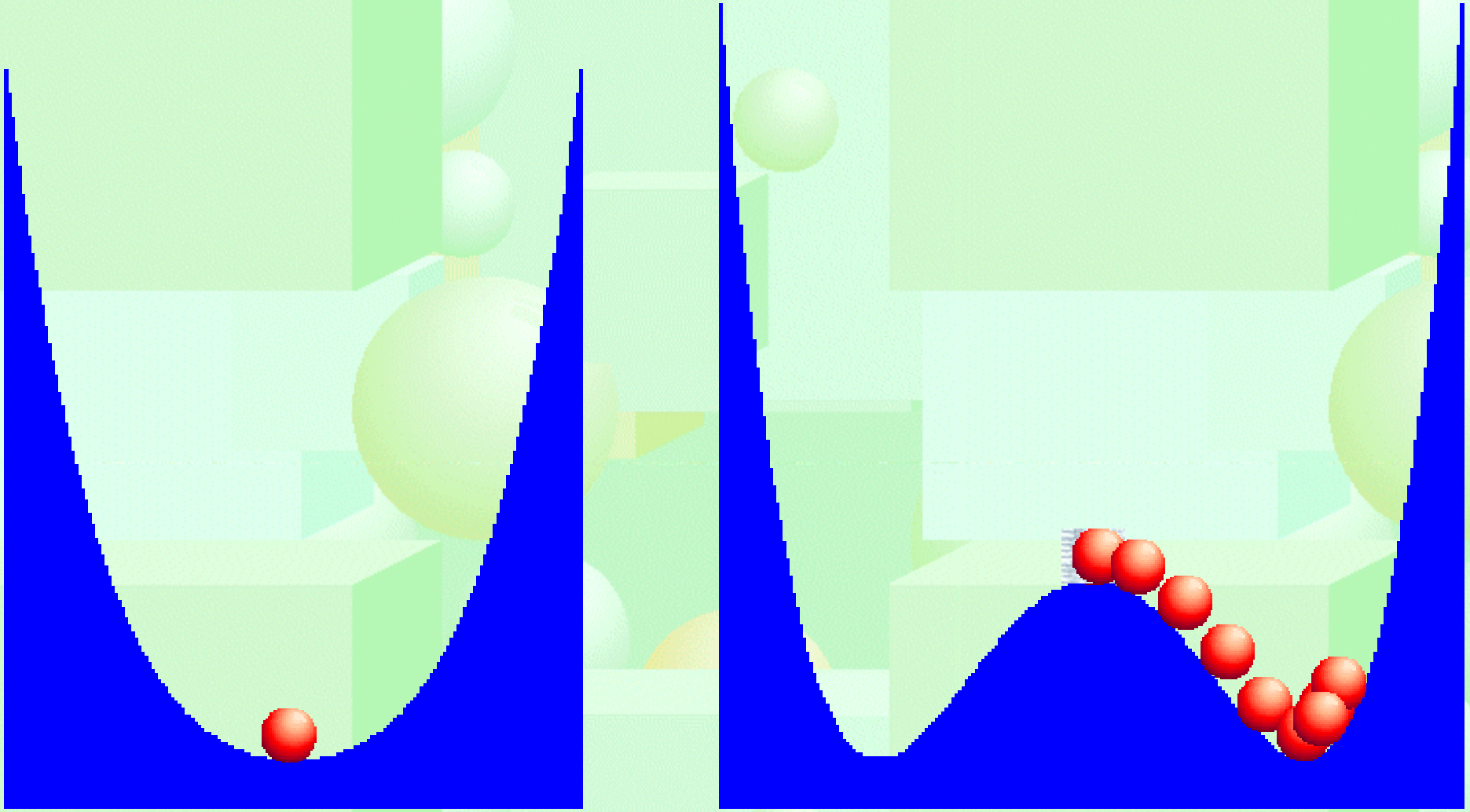
Time	"Size"	Energy/part.	Temperature	Era
10^{-43} sec	10^{-33} cm	10^{19} GeV	10^{32} K	Planck
10^{-35} sec	10^{-27} cm	10^{15} GeV	10^{28} K	Grand Unification
10^{-31} sec	1 cm	10^{13} GeV	10^{26} K	Inflation $\gg$
0.0001 μsec	10^{8} km	100 GeV	10^{15} K	Desert
1 μsec	10^{10} km	1 GeV	10^{13} K	Quarks + Leptons
0.1 msec	10^{11} km	100 MeV	10^{12} K	Hadrons
10 sec	0.1 ly	300 keV	$3 \cdot 10^{9}$ K	Leptons
15 min	1 ly	30 keV	$3 \cdot 10^{8}$ K	Nucleosynthesis
10 000 yr	10^{6} ly	2 eV	20 000 K	Radiation
300 000 yr	10^{7} ly	0.35 eV	3500 K	Plasma
10^{10} yr	10^{10} ly	10^{-4} eV	3 K	Matter

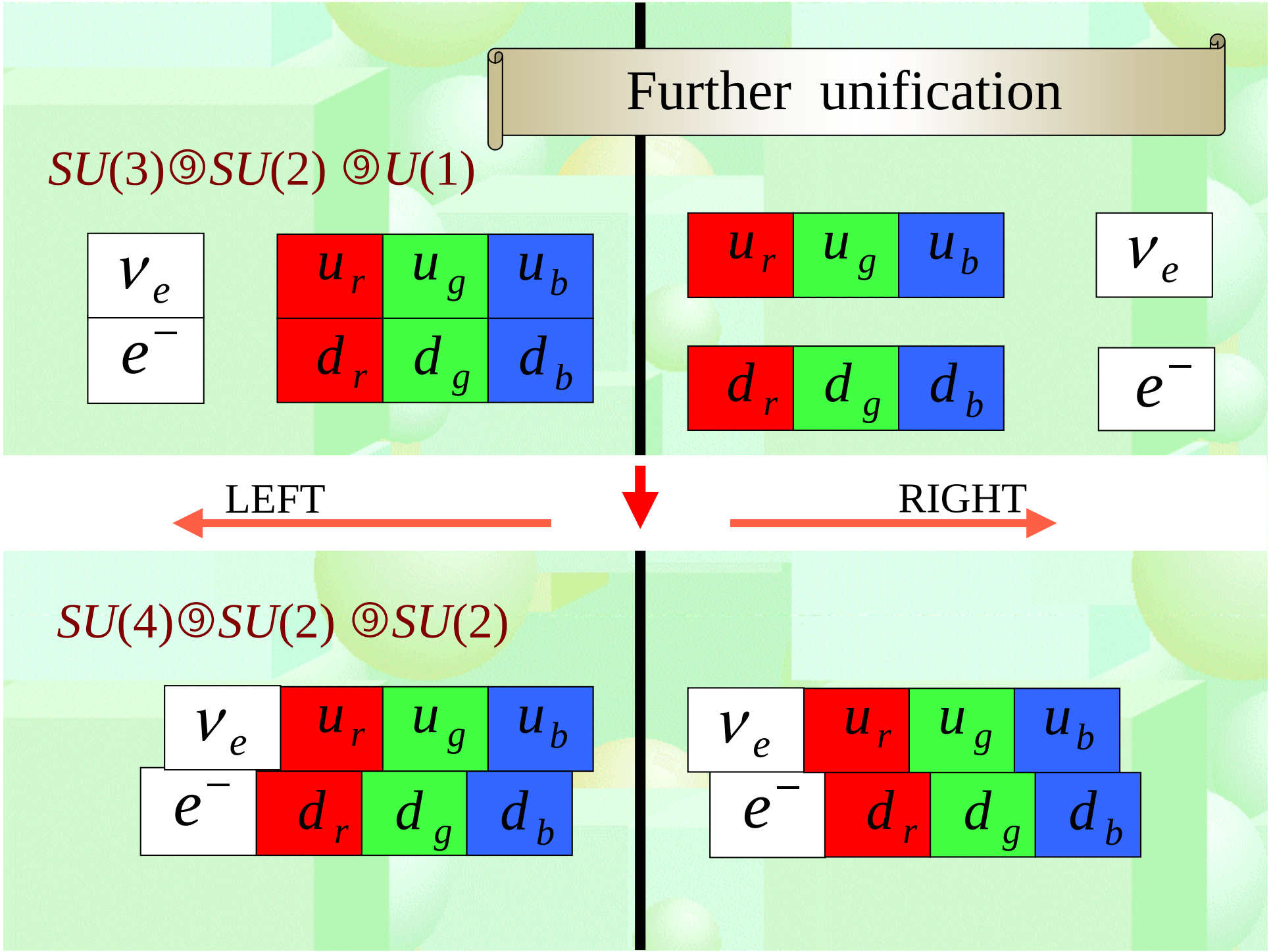

00-03-29
B150A 1dps
-421.
421.uK
-400
-200
0
200
400
b = -20
-40
-45
-50
Dec [Deg]
80
90
100
RA [Deg]

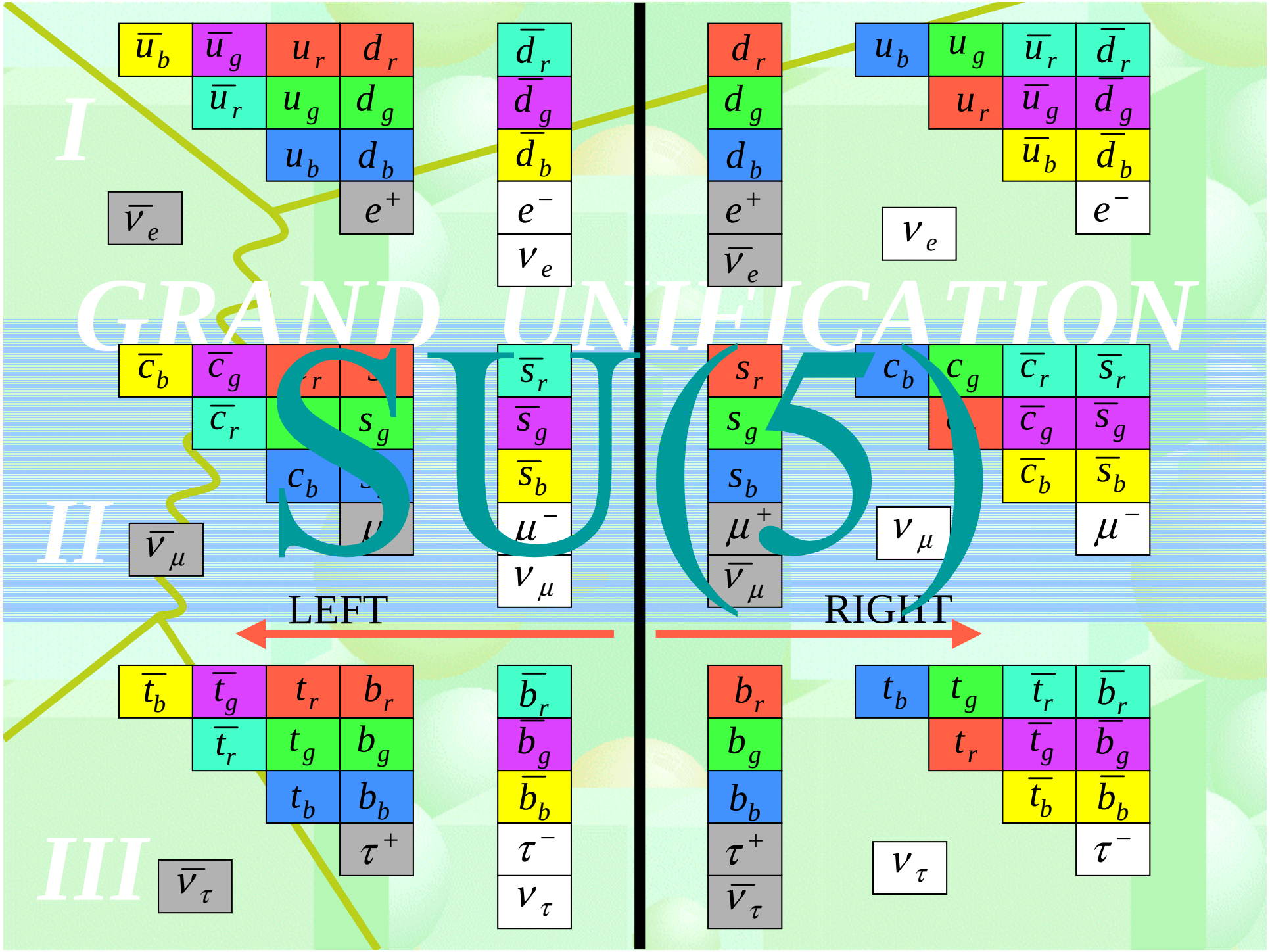

6000
4000
2000
0
0
200
400
600
800
1000
ℓ
$\ell(\ell+1)C_\ell/2\pi$ $[\mu K]^2$
weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98

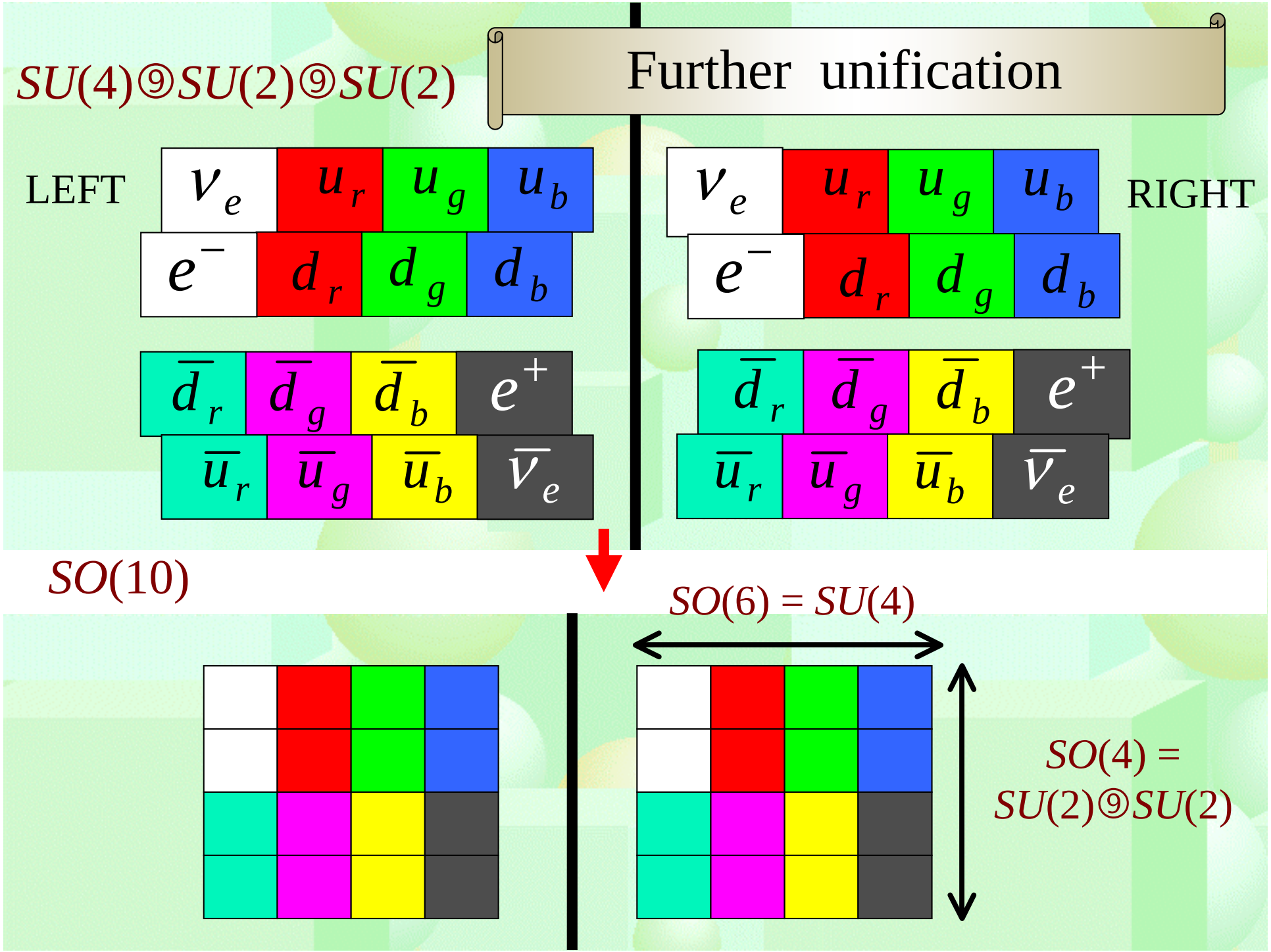

THE END
A Lecture
by
GERARD
't HOOFT
Utrecht
University
Utrecht University

Spontaneous symmetry breaking
(Brout, Englert, Higgs, Kibble, 1964)



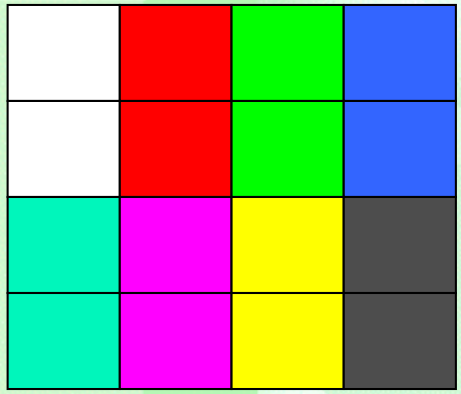

Further unification
SU(3)⊗SU(2) ⊗U(1)
ν_e
e^-
u_r u_g u_b
d_r d_g d_b
u_r u_g u_b
d_r d_g d_b
ν_e
e^-
LEFT
RIGHT
SU(4)⊗SU(2) ⊗SU(2)
ν_e u_r u_g u_b
e^- d_r d_g d_b
ν_e u_r u_g u_b
e^- d_r d_g d_b

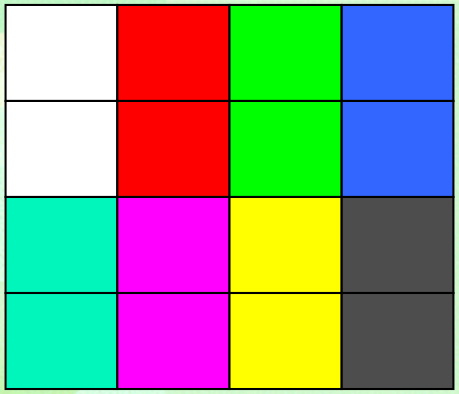

GRAND UNIFICATION
SU(5)
I
II
III
LEFT
RIGHT


SU(4)⊕SU(2)⊕SU(2)
Further unification
LEFT
RIGHT
SO(10)
SO(6) = SU(4)
SO(4) = SU(2)⊕SU(2)

3 generations

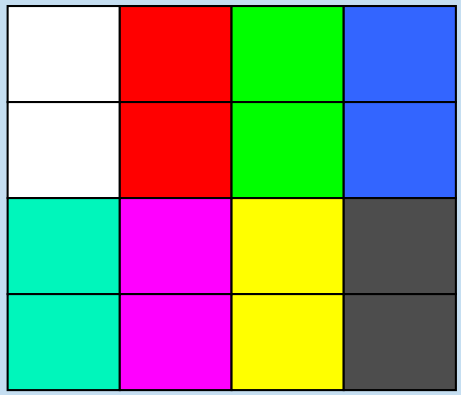
I

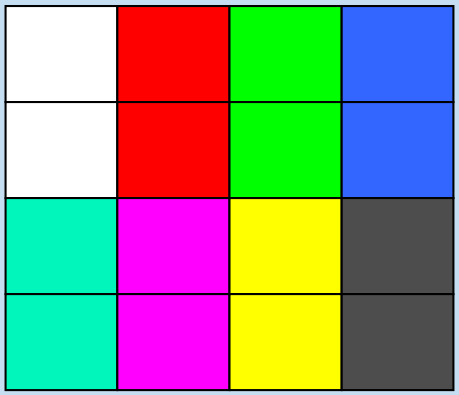




u, d, e

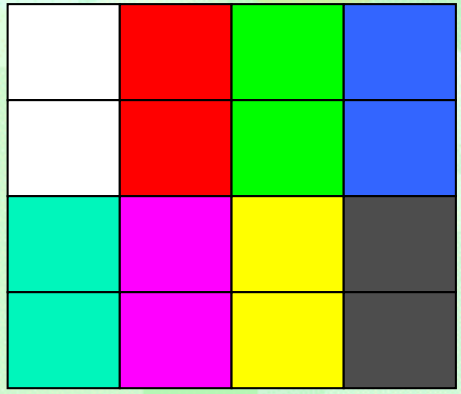
II

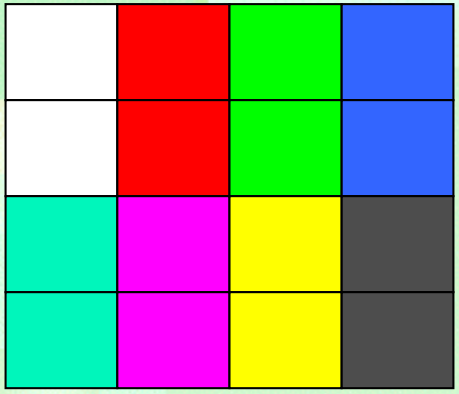




c, s, μ

III





t, b, τ

Super Symmetry

Spin around z-axis

-2 -1½ -1 -½ 0 ½ 1 1½ 2

$N = 1$ 1 1 1 1 1 1 1 1

$N = 2$ 1 2 1 1 2 1 1 2 1

$N = 4$ 1 4 6 4 1

SUSY

$N = 1$ 1 1 1 1

$N = 2$ 1 2 1 1 2 1

$N = 4$ 1 4 6 4 1 1 4 6 4 1

$N = 8$ 1 8 28 56 70 56 28 8 1

SUGRA