STRUCTURE OF MATTER

Discoveries and Mysteries

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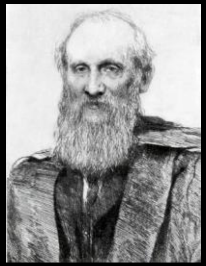
CERN

PREFACE

This is a lecture about 100 years of particle physics.
It covers about 100 years of ideas, theories and experiments.

More than 50 Nobel prize winners on particle physics
This is a broad overview about the main discoveries.

In the early 1900s, most physicists believed that physics was complete, described by classical mechanics, thermodynamics, and the Maxwell theory.



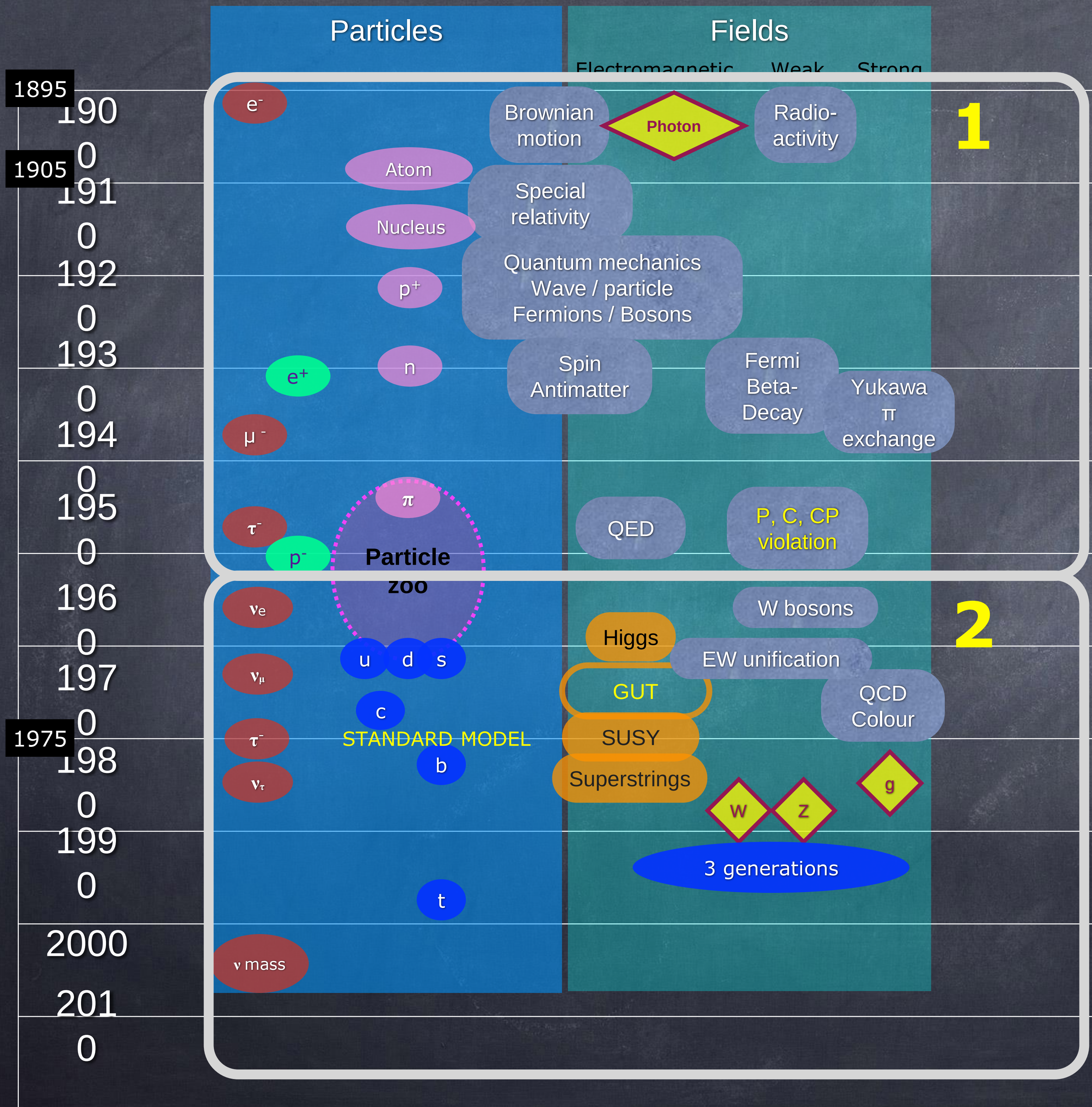
Lord Kelvin

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. " (Lord Kelvin, 1900)

DARK CLOUDS:

1) Blackbody radiation - Quantum Physics

2) Michelson-Morley experiment - Special Relativity


Particles
Fields
Electromagnetic
Weak
Strong
1895
1905
1975
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
e⁻
Brownian motion
Photon
Radio-activity
1
Atom
Special relativity
Nucleus
Quantum mechanics
Wave / particle
Fermions / Bosons
p⁺
e⁺
n
Spin
Antimatter
Fermi
Beta-Decay
Yukawa
π
exchange
μ⁻
π
QED
P, C, CP violation
τ⁻
p⁻
Particle zoo
νe
W bosons
2
Higgs
EW unification
u
d
s
νμ
GUT
QCD
Colour
c
τ⁻
STANDARD MODEL
SUSY
b
ντ
Superstrings
g
W
Z
3 generations
t
ν mass

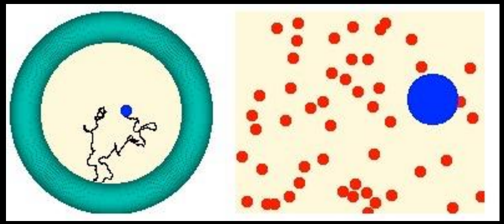
MATTER IS MADE OF PARTICLES

J.J. Thomson

1897: ELECTRON - the first 'discrete' building block of matter

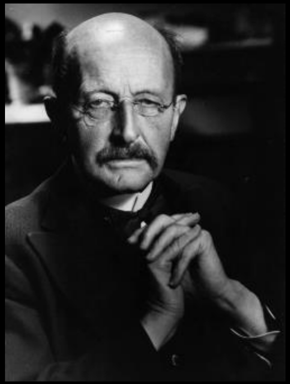
A. Einstein

1905: ATOMS ARE REAL - Explanation of Brownian Motion (Perrin)



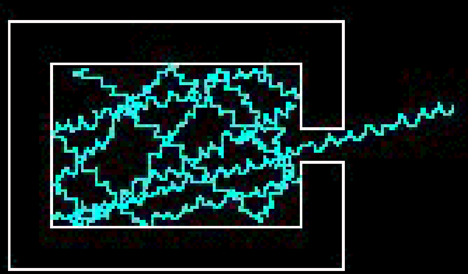
$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$

ENERGY COMES IN QUANTA



M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA



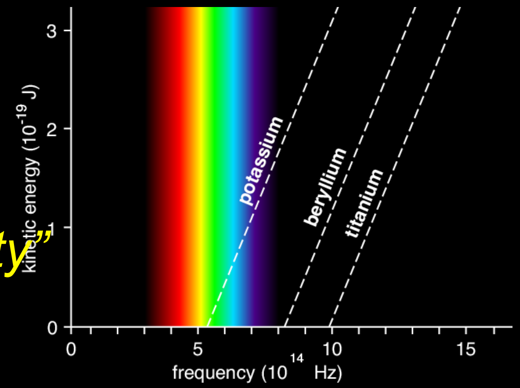
$$\varepsilon = h\nu$$

$$I(\nu) \sim \nu^2 \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

P. von Lenard

1902: PHOTOELECTRIC EFFECT

"The electron energy does not show the slightest dependence on the light intensity"



A. Einstein

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

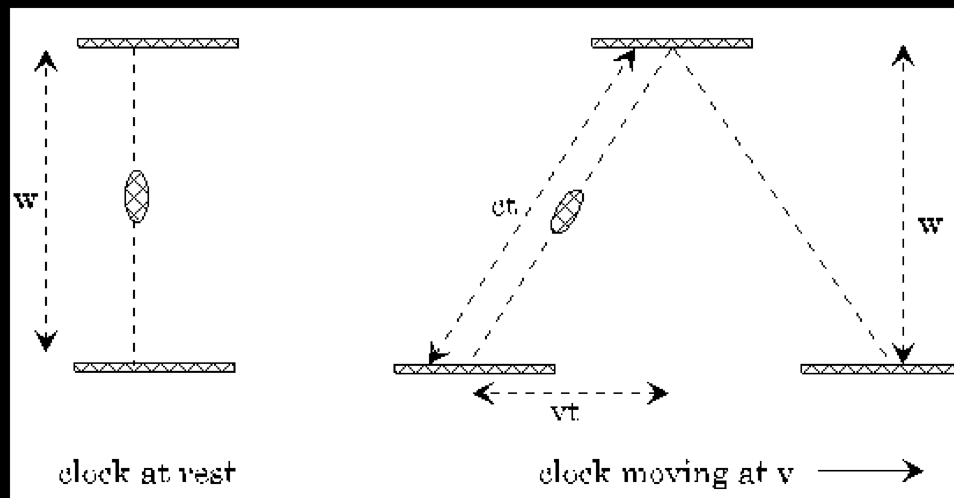
$$E_{max} = h\nu - W$$

"My only revolutionary contribution to physics"

SPECIAL RELATIVITY

A. Einstein

1905: SPEED OF LIGHT IS ALWAYS CONSTANT



$c^2t^2 = v^2t^2 + w^2$

$$t = \frac{w/c}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma \cdot \tau$$

1) Time dilation, space contraction

2) Modification of Newton's laws, relativistic mass increase.

$E=mc^2$

THE BEGINNING OF ATOMIC PHYSICS

Rutherford

1909: NUCLEI: very small + heavy within (almost) empty atom

Hydrogen

1913: BOHR MODEL- (empirical) explanation of discrete spectral lines

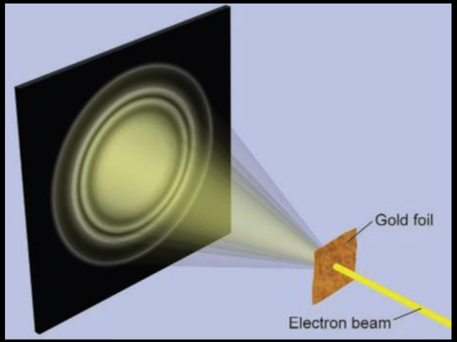
(using Planck's constant h) to quantize angular momentum

L. de Broglie

1923: DE BROGLIE

Particles are waves

$$\lambda = \frac{h}{p}$$



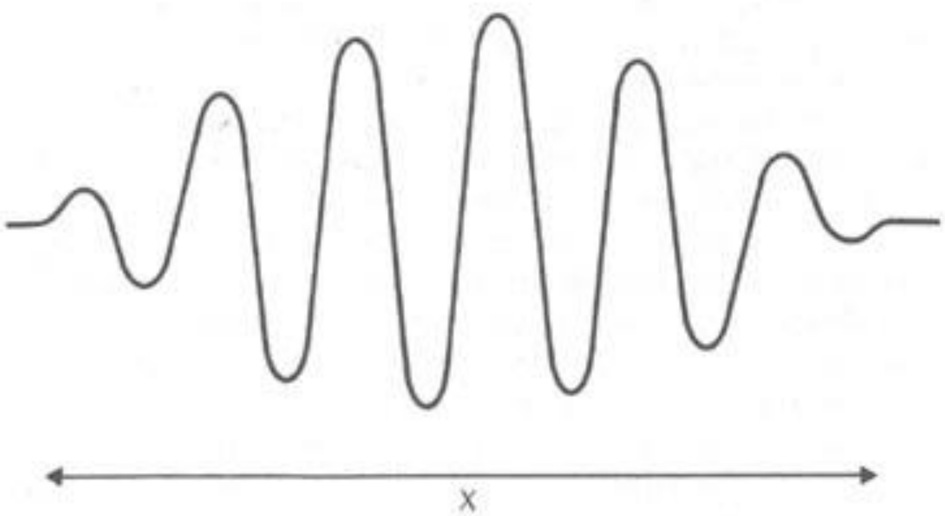
QUANTUM MECHANICS

Heisenberg

1923: UNCERTAINTY RELATION

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta t \geq \hbar$$



a wave packet corresponding to a particle located somewhere in the region X

From classical to quantum mechanics

Energy E of a particle with mass m, momentum p, in a potential $V(r)$

$$E = \frac{p^2}{2m} + V(r)$$

Total energy = kinetic + potential energy

How to translate from particle to wave language?

A wave is described by a spatial function $\psi(x)$ with circular frequency $\omega = 2\pi\upsilon$ and wave vector $\vec{k} = 2\pi / \lambda$

$$\psi(\vec{x}) = Ae^{i(\vec{k}\vec{x}-\omega t)}$$

De Broglie momentum of a "particle wave":

$$p = \frac{h}{\lambda} = \frac{h}{2\pi} \cdot \frac{2\pi}{\lambda} = \hbar k$$

Energy of a "particle wave":

$$E = h\upsilon = \frac{h}{2\pi} 2\pi\upsilon = \hbar\omega$$

$p = \hbar k$

$$\psi(\vec{x}) = Ae^{i(\vec{k}\vec{x}-\omega t)}$$

Get momentum using gradient:

$$-i\hbar\nabla\psi = -i\hbar(i\vec{k}\psi) = \hbar\vec{k}\psi$$

$$\vec{p} \rightarrow -i\hbar\vec{\nabla}$$

$$E = \hbar\omega$$

$$\psi(\vec{x}) = Ae^{i(\vec{k}\vec{x}-\omega t)}$$

Get energy using time derivative:

$$i\hbar\frac{\partial}{\partial t}\psi = i\hbar(-i\omega\psi) = \hbar\omega\psi$$

$$E = i\hbar\frac{\partial}{\partial t}$$

$$E = \frac{p^2}{2m} + V(r) \qquad E \to i\hbar \frac{\partial}{\partial t} \qquad \vec{p} \to -i\hbar\vec{\nabla}$$

Schrödinger equation:

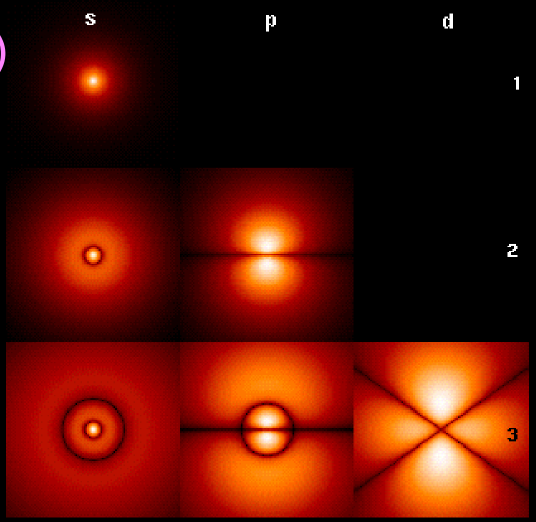
$$i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2\nabla^2}{2m}\psi + V(r)\psi$$

Schrödinger

1926: SCHRÖDINGER EQUATION

$$H\psi(\mathbf{r},t) = (T+V)\,\psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\psi(\mathbf{r},t) = i\hbar\frac{\partial\psi}{\partial t}(\mathbf{r},t)$$

(electrons in atoms form ‘standing waves’)



Interpretation (Born, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability

RELATIVISTIC QUANTUM MECHANICS

Paul A.M. Dirac
(1928)

$$E^2 = p^2 + m^2 \rightarrow$$

$$E = \pm(\alpha \cdot p) + \beta m$$

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0$$

$$\Psi = \begin{pmatrix} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{pmatrix}$$

Spin

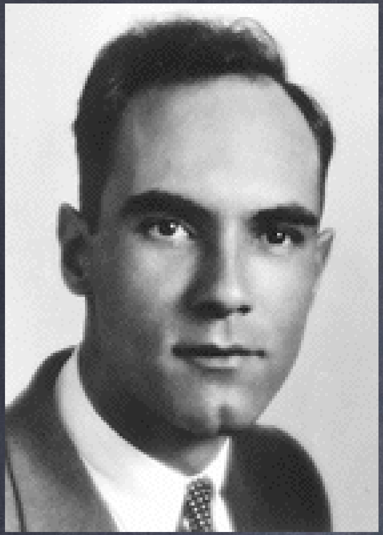
Antimatter

ELECTRON SPIN 1/2 EXPLAINED

ANTIPARTICLES MUST EXIST !

SPIN 1/2 PARTICLS (FERMIONS) MUST OBEY EXCLUSION PRINCIPLE

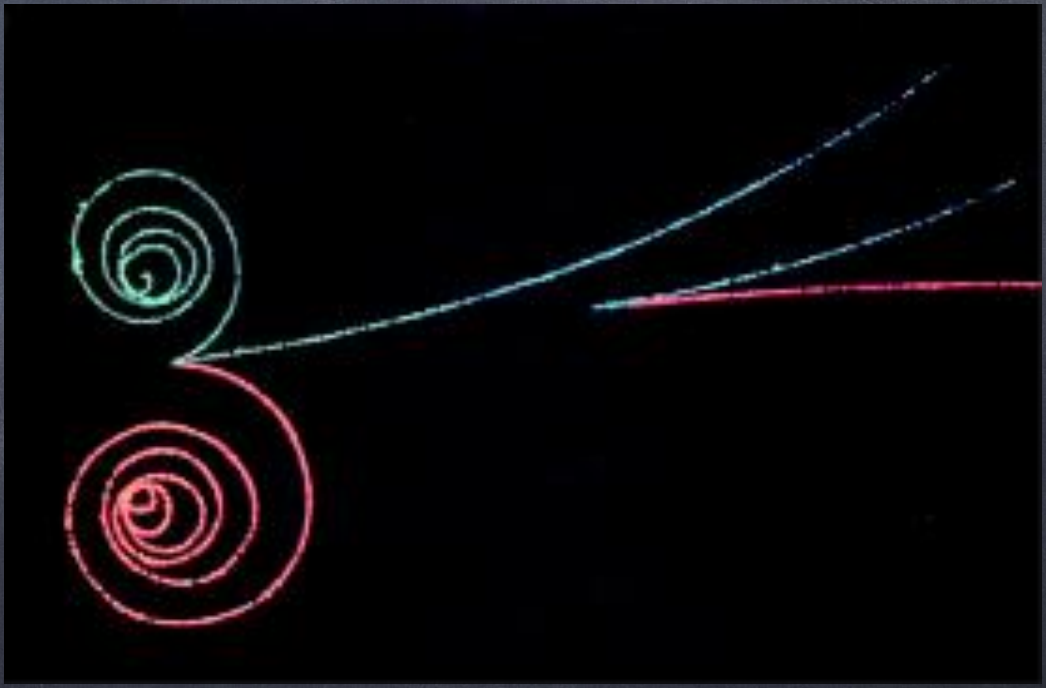
ANTIPARTICLES



Anderson

1932: POSITRON DISCOVERY

EVERY PARTICLE HAS AN ANTIPARTICLE

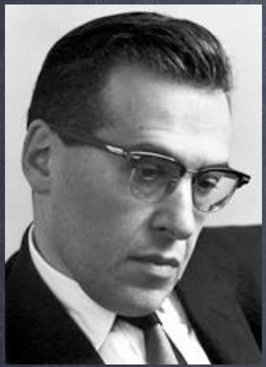


WHEN ENERGY CONVERTS TO MASS,
PARTICLES AND ANTIPARTICLES ARE PRODUCED

QUANTUM FIELD THEORY (1927 - 1948)

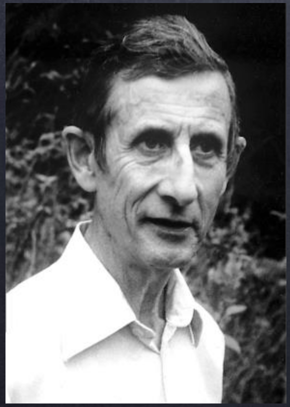
S.I. Tomonaga

It was known that the **electromagnetic field consists of photons**



J. Schwinger

How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?

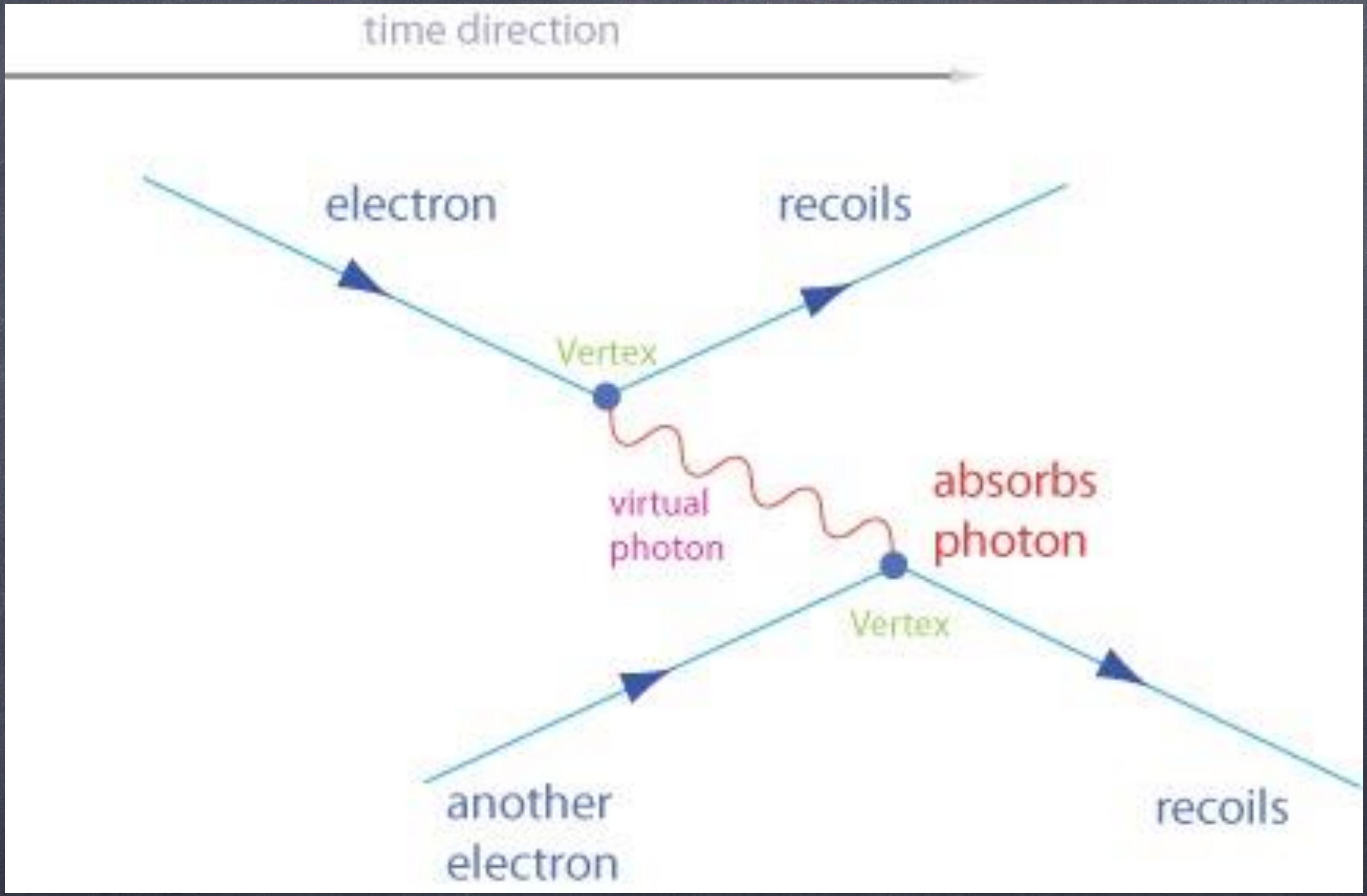


F. Dyson

Many people worked on this problem ...

Quantum Electrodynamics (QED)

R.P. Feynman

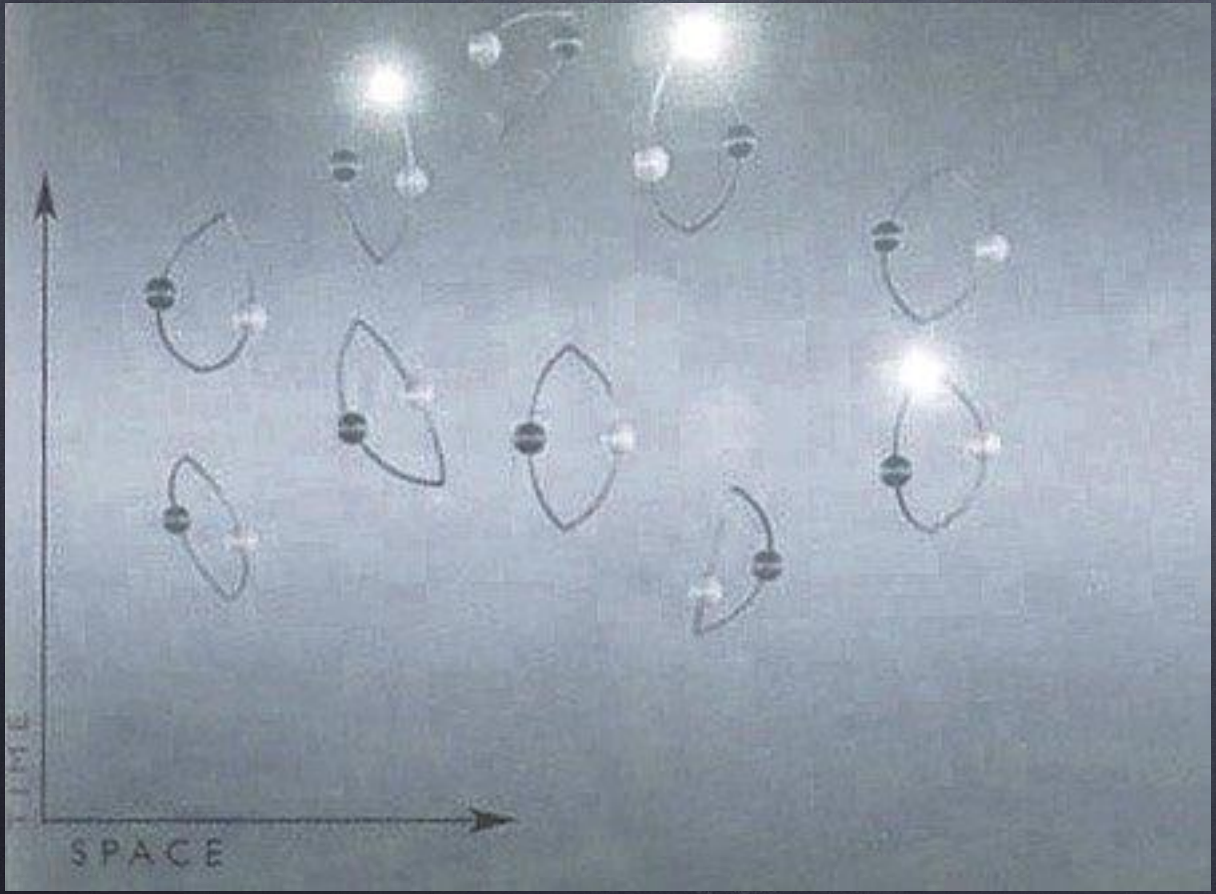


VACUUM FLUCTUATIONS

Quantized fields: Ground state energy is ≠ 0

Photons and particle-antiparticle-pairs populate empty space !

[Remark: should give rise to (lots of) "vacuum energy"]



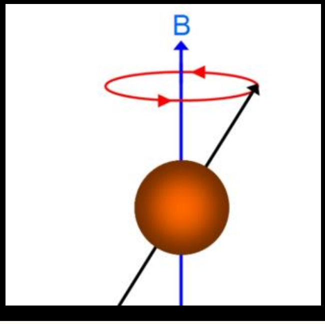
UNCERTAINTY RELATION:

$\Delta E \times \Delta t \geq h/2\pi$

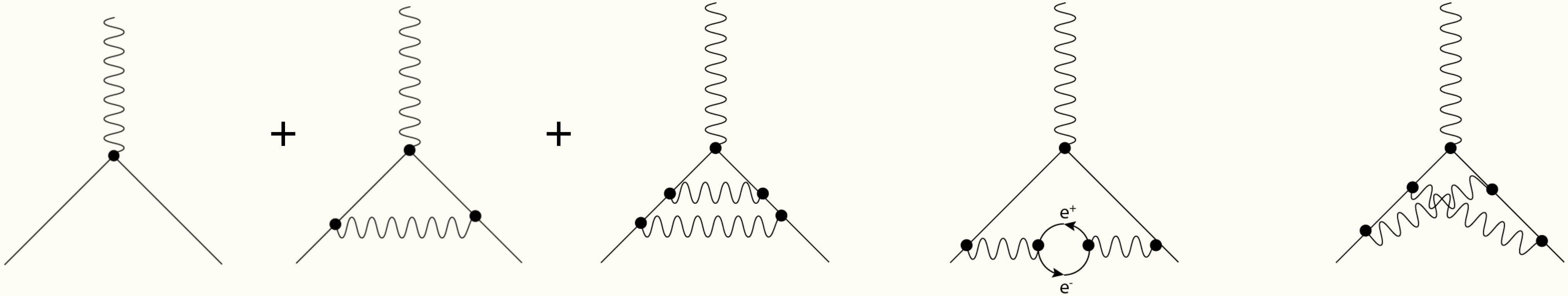
Vacuum fluctuations have observable effects

The world record for the most precise calculation in physics goes to:

Electron anomalous magnetic moment "g"



$$\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{S}$$



"Leading order"

Second order

Fourth order corrections

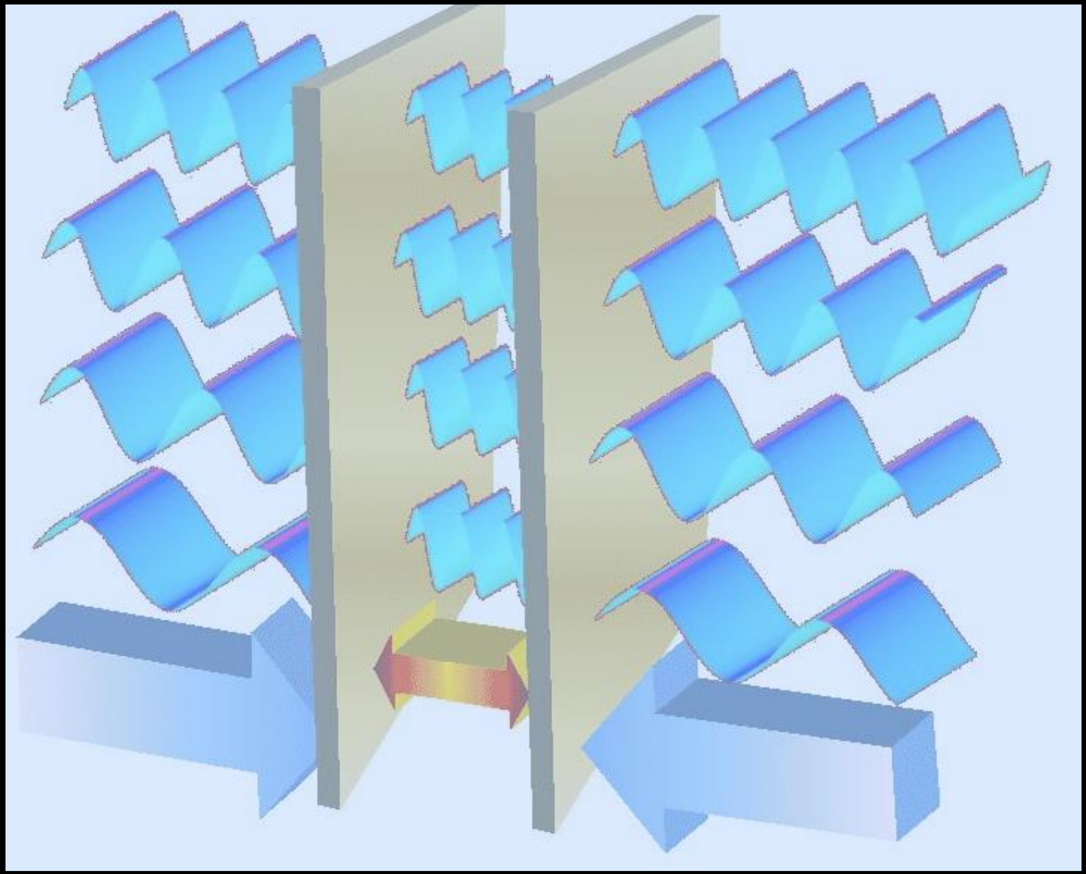
g = 2

a = (g-2)/2 = 1/2π * 1/137

~ 0.0011614

Current precision (theory and experiment agree!)
a = 0.00115965218073(28)

CASIMIR EFFECT



$$p_c = \frac{F_c}{A} = \frac{\hbar c \pi^2}{240 \cdot d^4}$$

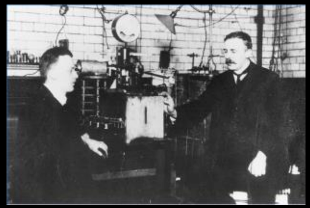
p = 100 kPa (d=11 nm)

SPOOKY: at 11 nm distance, the pressure is 1 atm.

NUCLEAR PHYSICS

M. Curie

1895-1900: RADIOACTIVITY - strange radiation phenomena



E. Rutherford

1903: Alpha-, Beta-, Gamma-Radiation known

(different penetration depth)

1911: Nucleus positive, small - surrounded by electrons

J. Chadwick

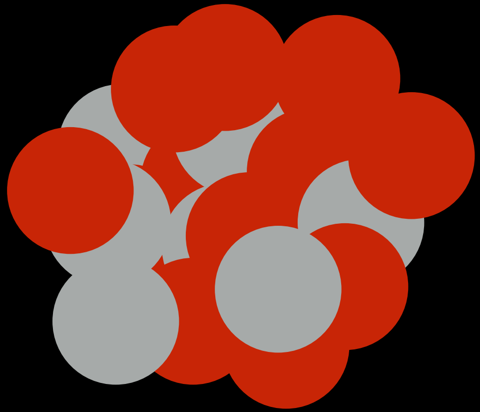
1932: DISCOVERY OF THE NEUTRON

Alpha particle = He nucleus

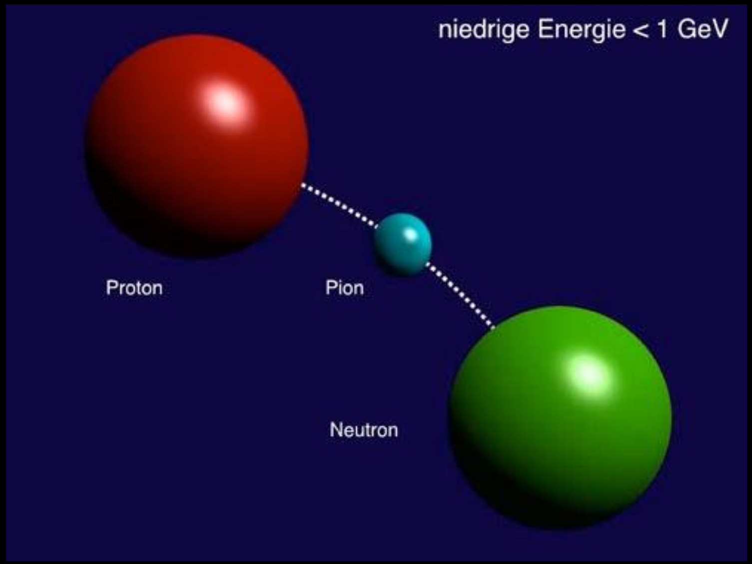
NUCLEAR PHYSICS - 1934

Yukawa (1934)

What keeps protons and neutrons together ?

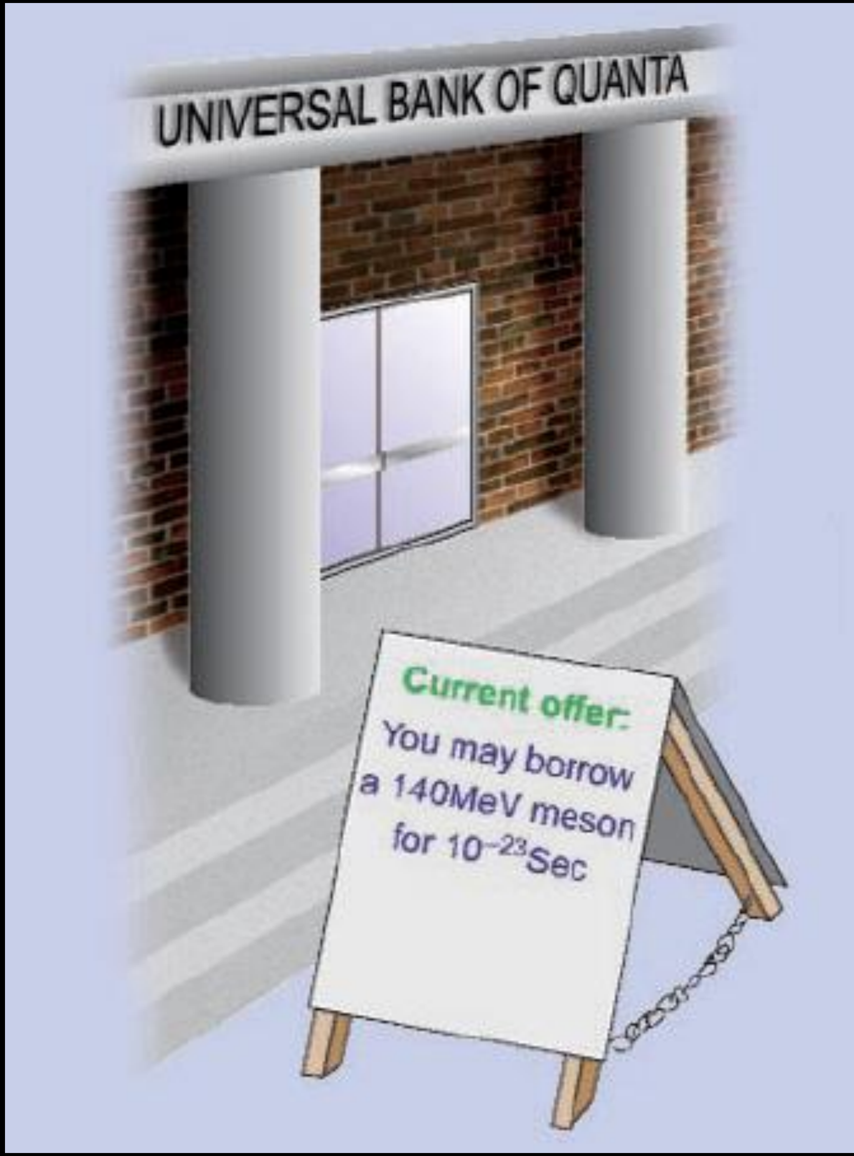


Why is the range of nuclear forces finite?
(maximum size of nuclei ~ 5 fm)



Yukawa model:

- New “strong” interaction
- Exchange of “pion”
- Pion has mass: finite range of 1-2 fm



Toy model:

UBS offers you a loan of

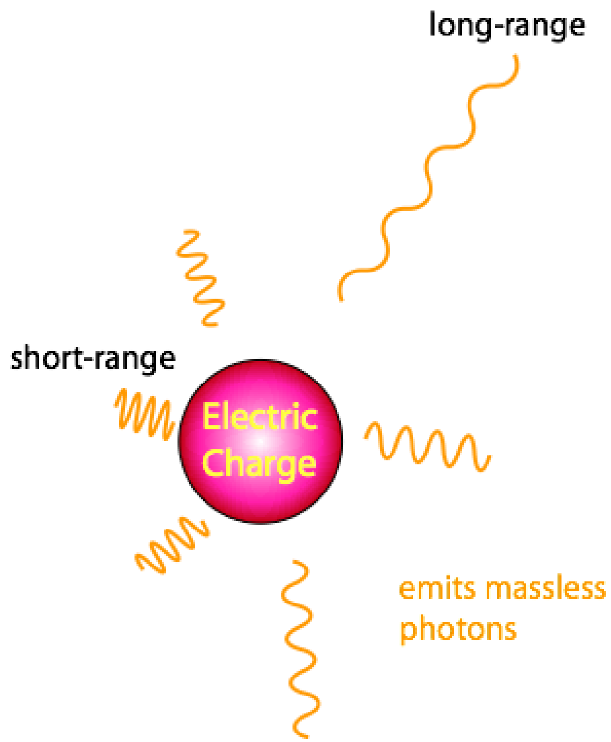
1000 Euro x Seconds

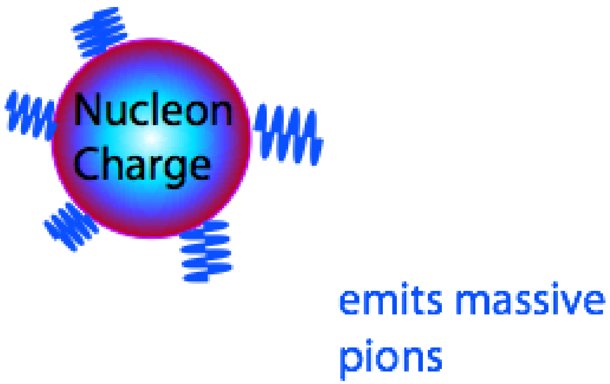
UNCERTAINTY RELATION:

$\Delta E \times \Delta t \geq h/2\pi$

Electromagnetic vs Nuclear

Exchange Forces





$$\Delta E\, \Delta t \geq \hbar \qquad (\Delta E \sim m)$$

$$r = c\, \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

$$V(r) = -e^2 \frac{1}{r}$$

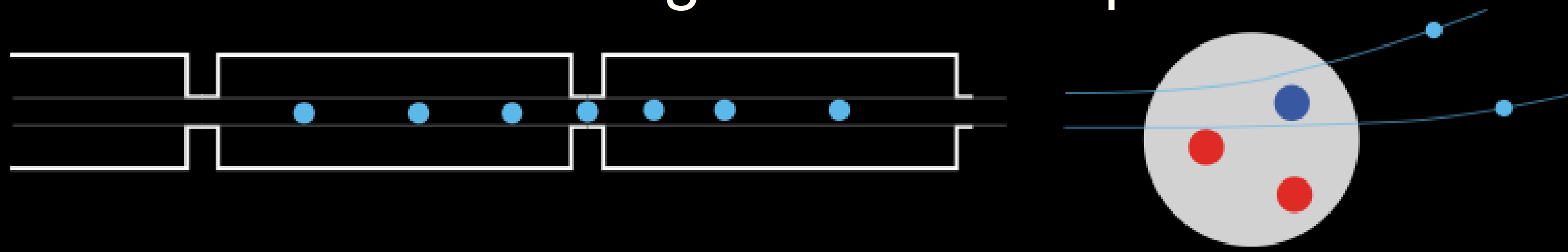
Coulomb law

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

Yukawa potential ~ Modified "Coulomb" law

QUARKS AND QCD

An accelerator is a giant microscope ….



… and can also produce new particles:

$E = mc^2$

1948 - 1960s: New accelerators and detectors

PARTICLE ZOO contains ~ 200 'elementary particles'

Mesons

π^{+} π^{-} π^{0}

Pions

K^{+} K^{-} K^{0}

Kaons

η'

Eta-Prime

η

Eta

φ

Phi

ρ^{+} ρ^{-} ρ^{o}

Rho

BARYONS

$\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}$

Delta

Λ^{0}

Lambda (strange!)

$\Sigma^{+}, \Sigma^{0}, \Sigma^{-}$

Sigma (strange!)

Ξ^{0}, Ξ^{-}

Sigma(very strange!)

Underlying structure ?

Classification scheme based on ‘quarks’

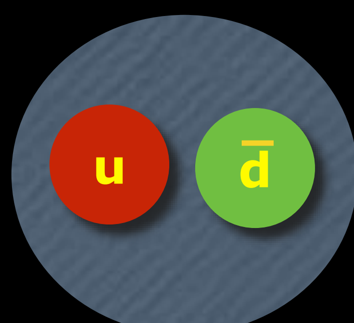
1963


Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963
(G. Zweig, 1963)

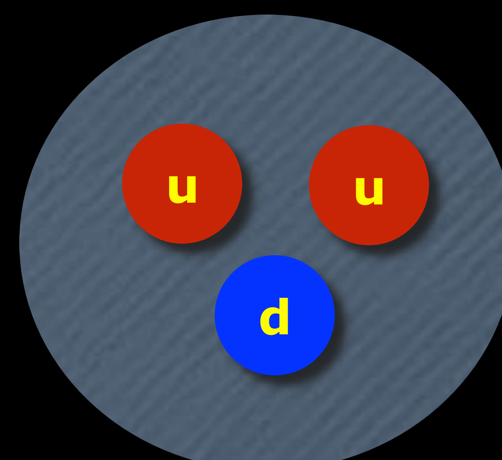
3 types of “quarks” : up, down, strange (and their anti-particles)

+2/3 -1/3 -1/3 electric charge



π^+

Meson



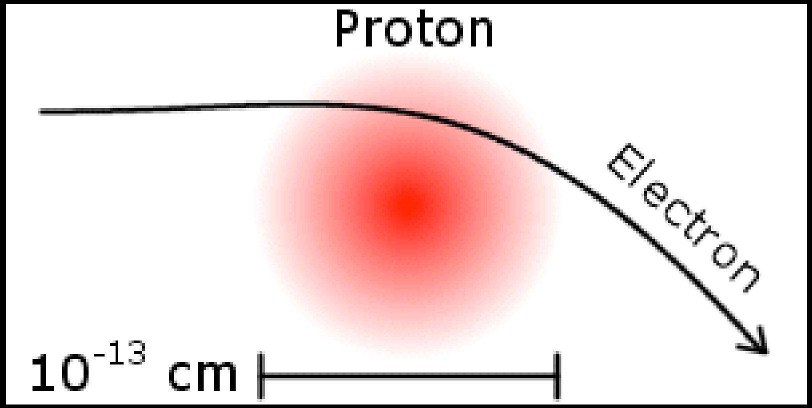
p

Baryon

Discovery of quarks

Electron-Proton scattering at Stanford

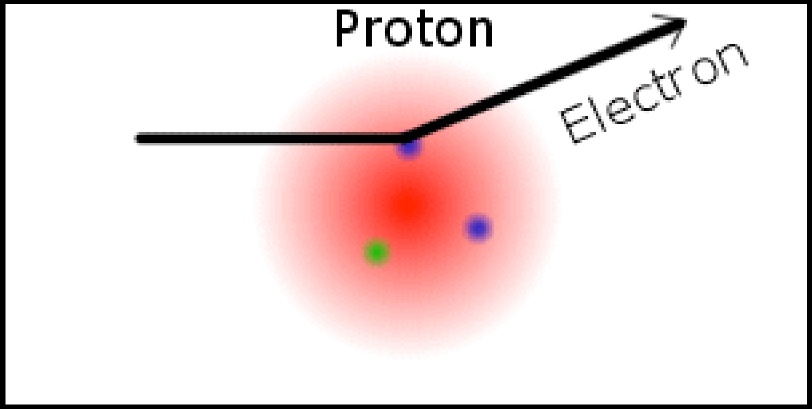
1956 Hofstadter: proton radius ~ 1 fm



E = 0.2 GeV

Stanford Linear Accelerator Centre

1967 Friedmann, Kendall, Taylor: three 'point-like particles' inside a proton



E = 20 GeV

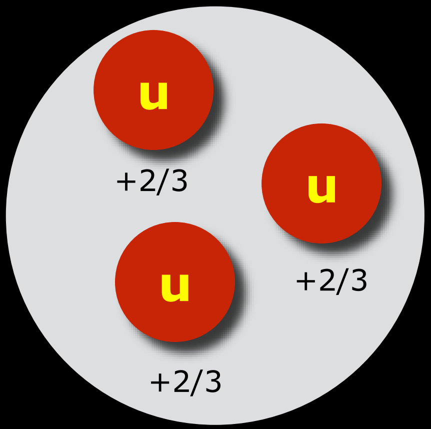
Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

The concept of "Colour" charge

How can you explain this particle ?

Δ^{++}

Spin = 3/2



three fermions are not allowed to be in the same quantum state (Pauli exclusion principle)

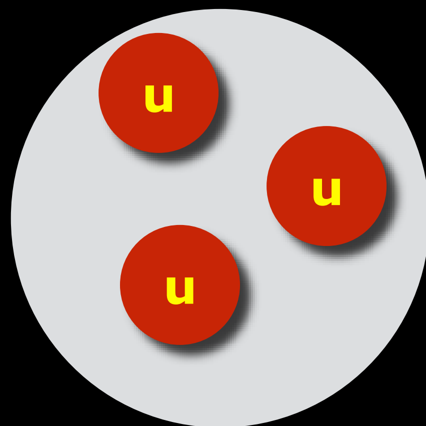
A new concept: "colour charge"

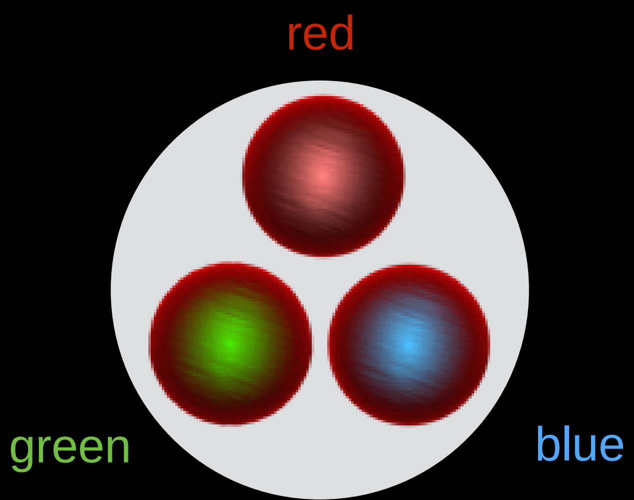
1) ***Colour charge is source of 'strong force'***
2) ***There are three types of colour (e.g. "red", "green", "blue")***
3) ***Only colour-neutral states can exist***

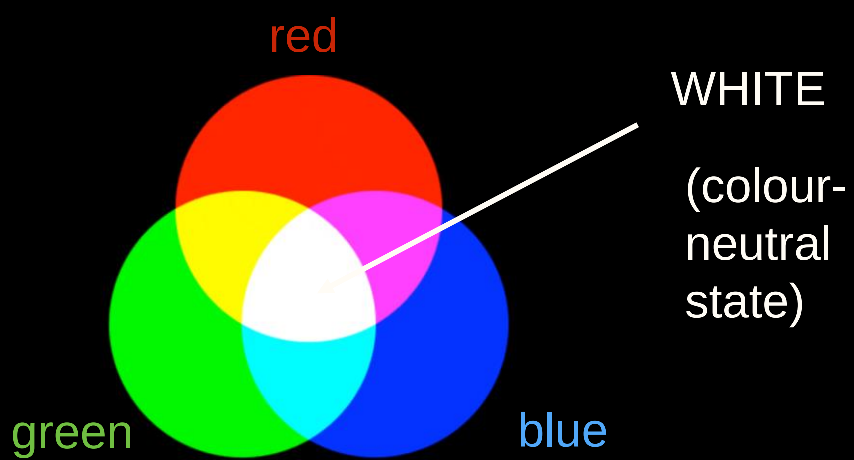
(Bardeen, Fritzsch, Gell-Mann)

Quarks carry a “colour” charge - in addition to their electric charge
(that makes them different and hence exclusion principle does not apply)

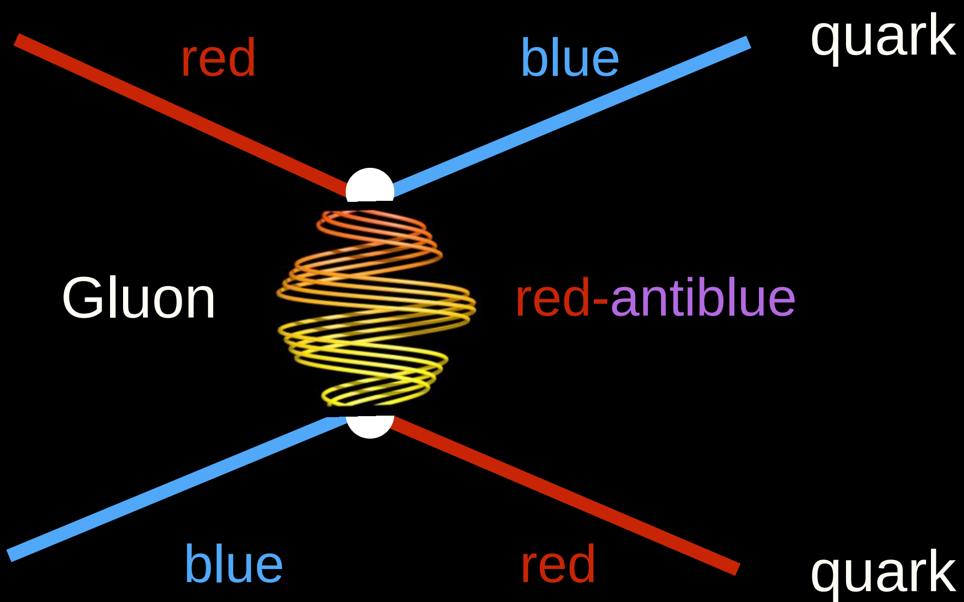
Δ^{++}

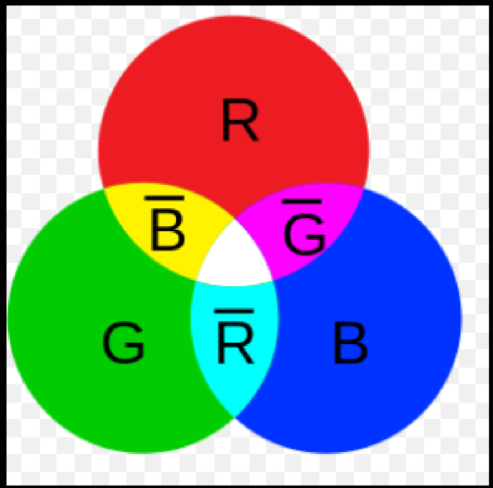






Quarks interact by exchanging 'gluons' that carry colour (and anti-colour)



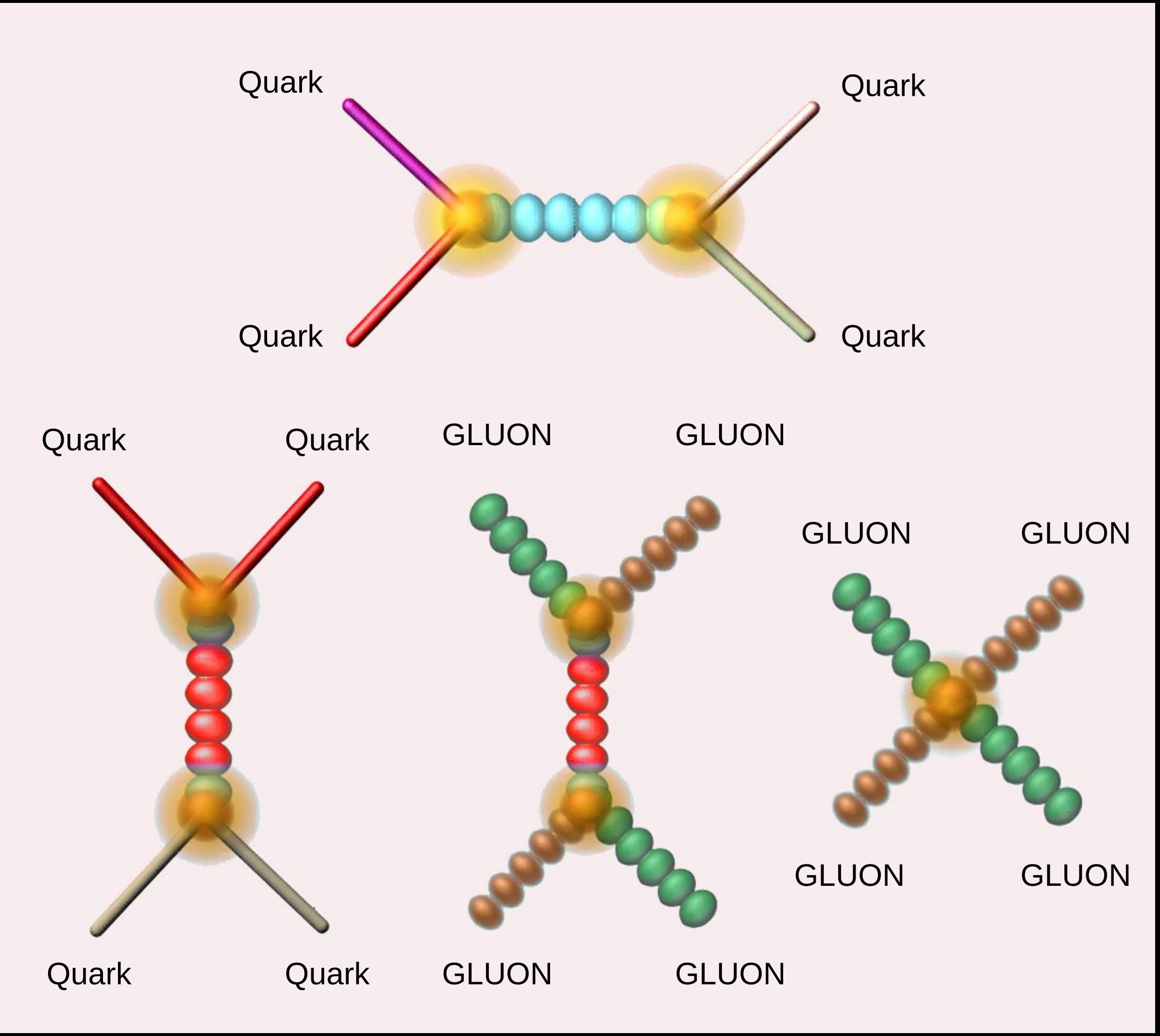


Total number of gluons: 3 x 3 - 1 = 8

(1 combination is a 'colour-singlet', i.e. neutral)

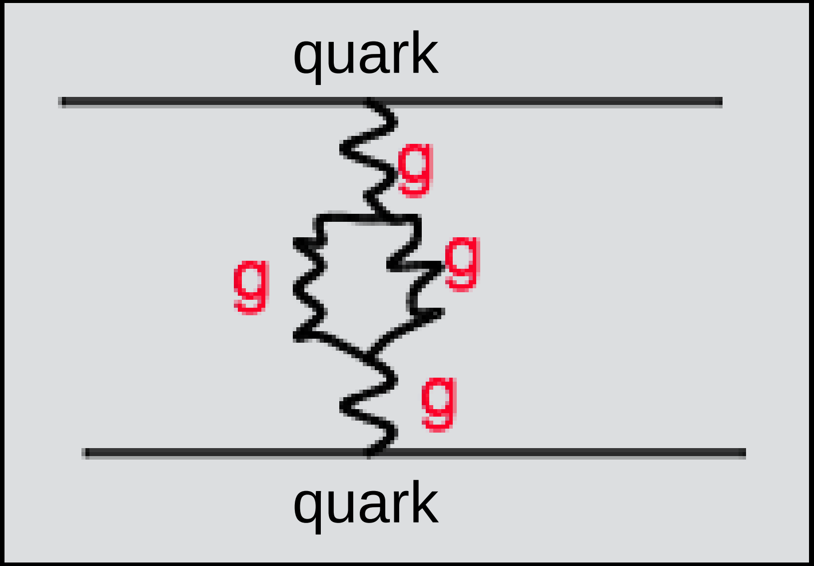
Since gluons carry a (colour) charge:

Gluons can interact with other gluons

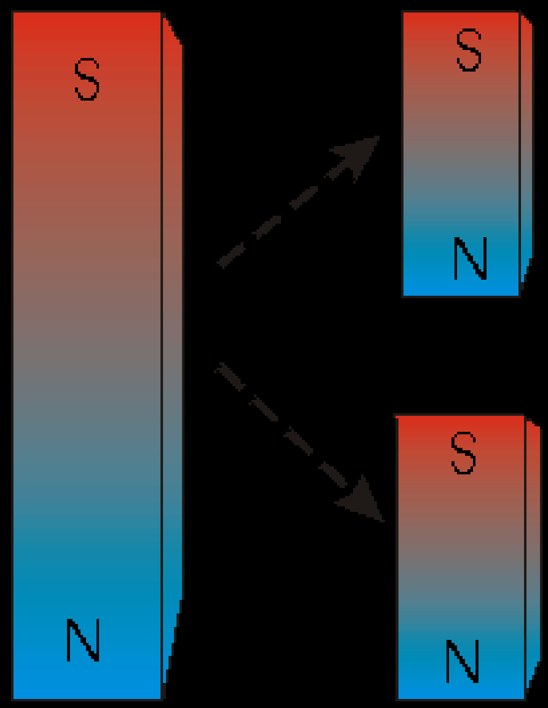


The self-interaction of the gluons results in the energy of the gluon string increasing with distance between quarks.

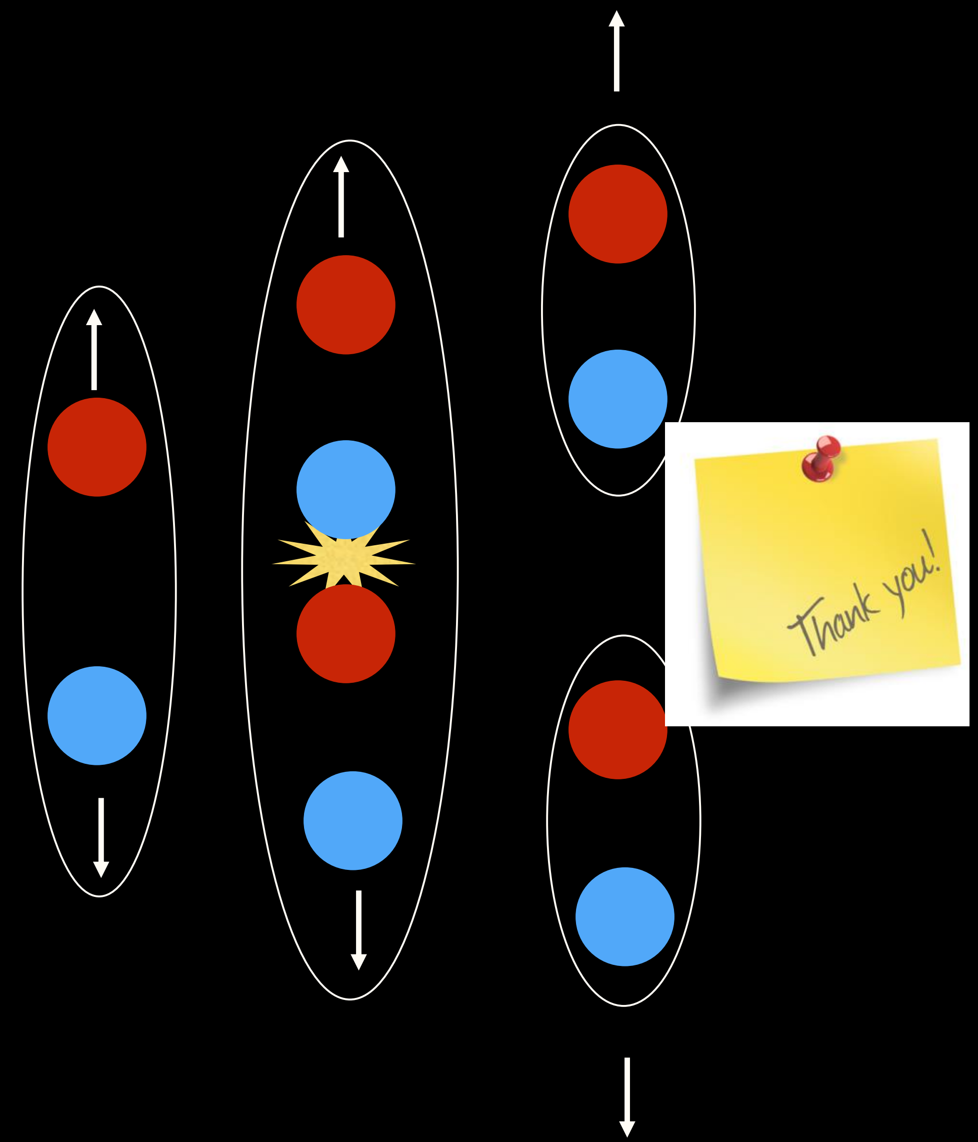
This produces a force that keeps the quarks as ‘prisoners’.



Gluon ‘strings’ break : new quark-antiquark pairs



Analogy to breaking a
magnet into two halves: does not
produce a magnetic monopole



Meson

excited
state of
meson

string breaking:
two mesons