

# **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.**

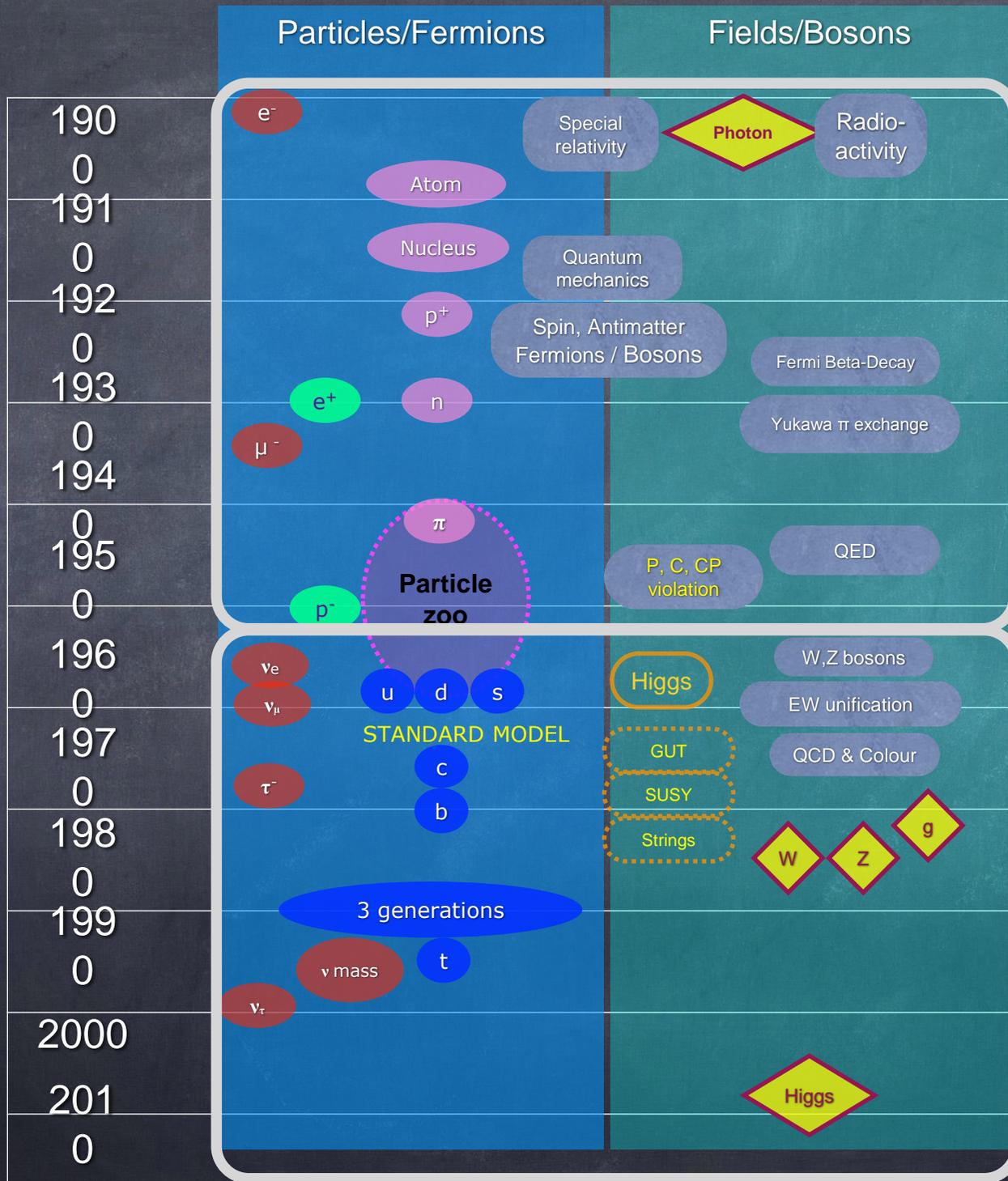


Lord Kelvin

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

**DARK CLOUDS:**  
1900)

- 1) Blackbody radiation - Quantum Physics
- 2) Michelson-Morley experiment - Special Relativity



1

2

# MATTER IS MADE OF PARTICLES



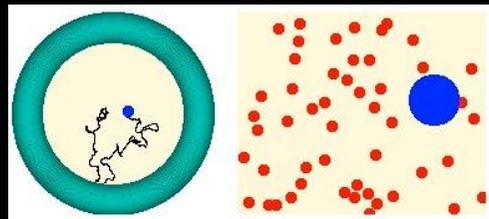
J.J. Thomson

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



A. Einstein

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



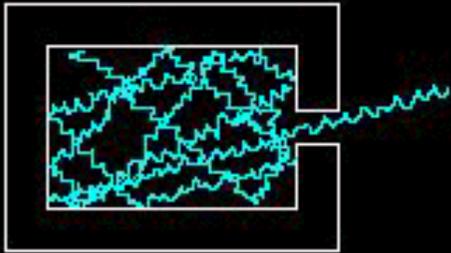
$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$

# ENERGY COMES IN QUANTA



M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA



$$\epsilon = h \nu$$

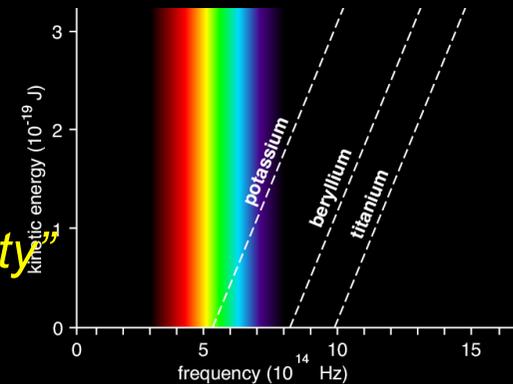
$$I(\nu) \sim \nu^2 \frac{h\nu}{e^{h\nu/kT} - 1}$$



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

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

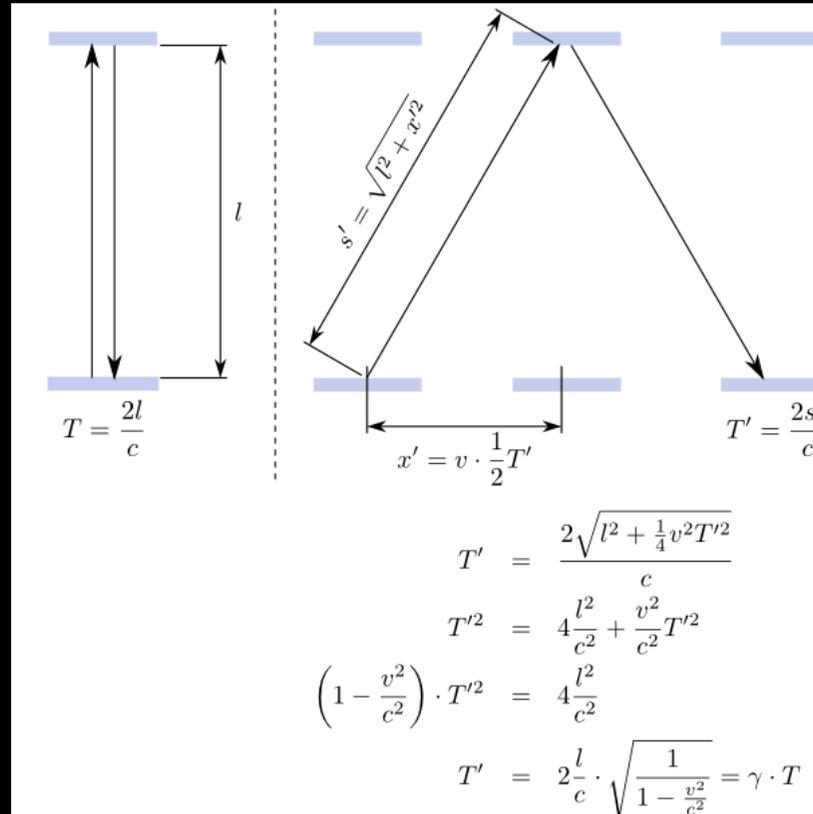
*“My only revolutionary contribution to physics”*

# SPECIAL RELATIVITY



A. Einstein

1905: SPEED OF LIGHT IS ALWAYS CONSTANT



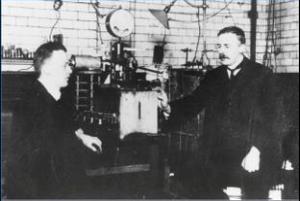
Time passes slower  
in moving reference frame

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

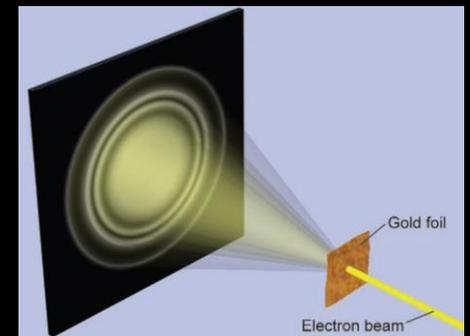


L. de Broglie

1923: DE BROGLIE

**Particles are waves**

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

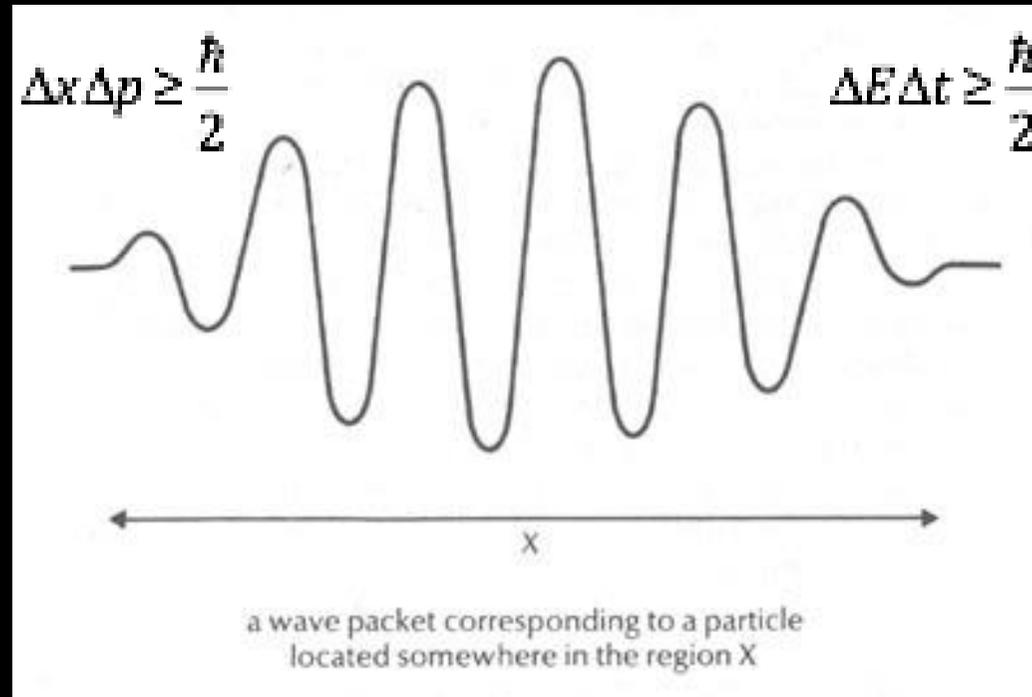


# QUANTUM MECHANICS



Heisenberg

## 1923: UNCERTAINTY RELATION



Fourier analysis of a wave packet (e.g. acoustics)

$$\Delta \omega \Delta t \approx 1$$

# INTERLUDE 1

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

(‘Hamiltonian’)

# How to translate from particle to wave language?

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

PLAIN WAVE:

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

De Broglie momentum of a “particle wave”:

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

$$p = \hbar k$$

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

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

Energy of a “particle wave”:

$$E = \hbar\omega$$

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

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

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

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

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

Schrödinger equation:

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

END OF INTERLUDE 1

# NON-RELATIVISTIC QUANTUM MECHANICS



Schrödinger

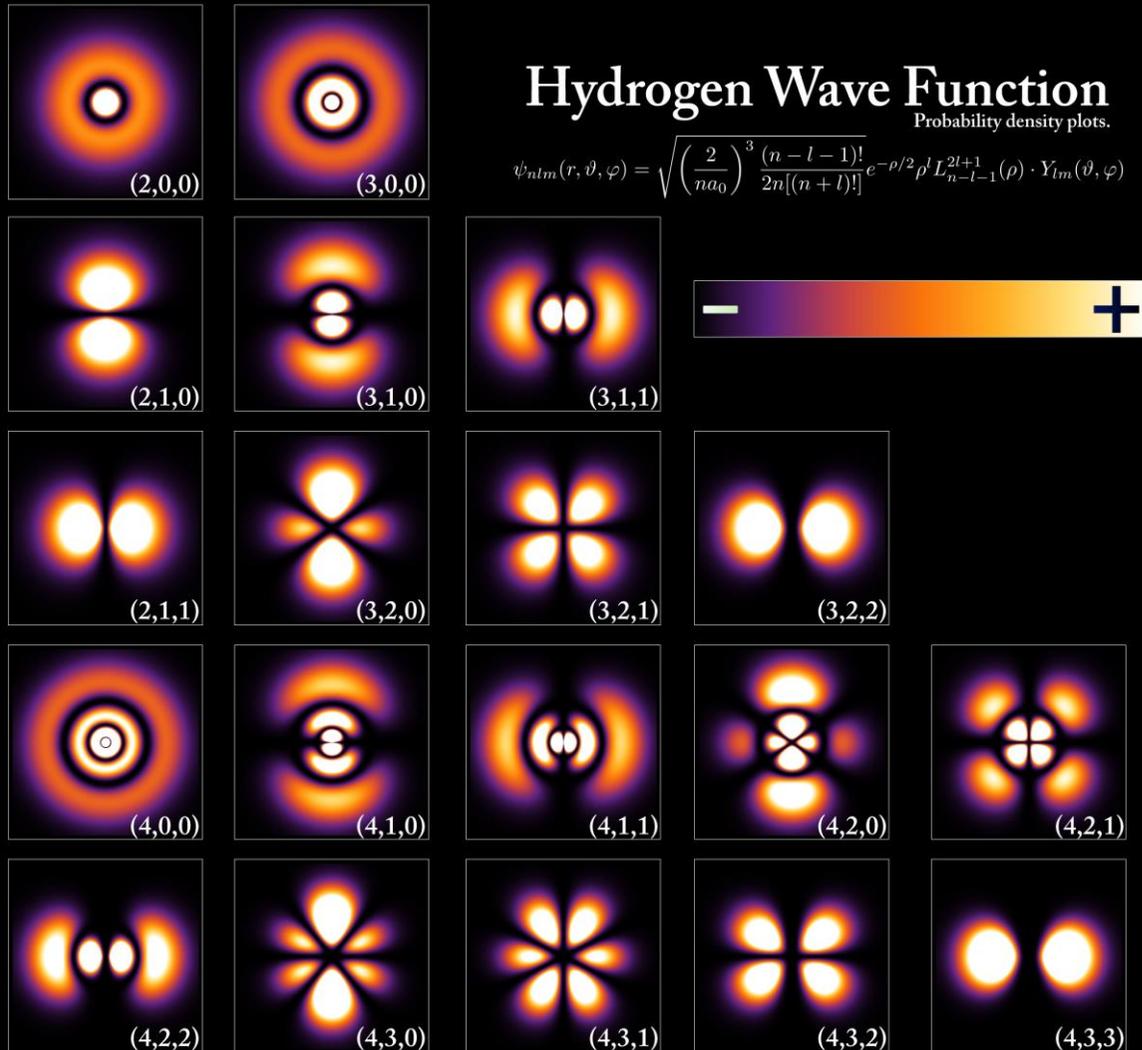
Atom = spherically symmetric Coulomb potential:  $V(r) \sim 1/r$

Wave function describes 'standing waves' (time independent)

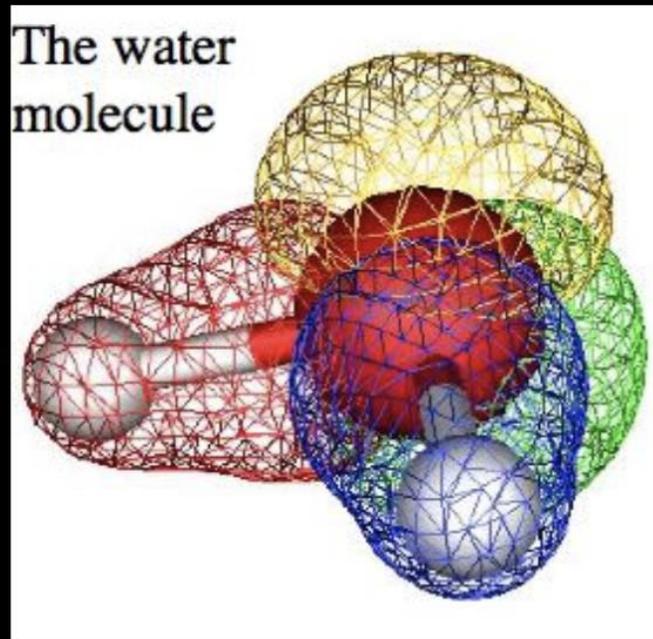
**Interpretation** (Born, 1927):

$\psi$  = probability amplitude

$|\psi|^2$  = probability



# THE ORIGIN OF SHAPE !



Linus Pauling, 1928

# INTERLUDE 2

But :  $E = \frac{p^2}{2m} + V(r)$  is only valid if  $v \ll c$



Quantum mechanics

Special Relativity

Relativistic quantum mechanics



Paul A.M. Dirac  
(1928)

Let's try (set  $\hbar = c = 1$ )

non-relativistic

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



relativistic

$$E^2 = p^2 + m^2 + V(r)$$

$E \rightarrow i \frac{\partial}{\partial t}$        $\vec{p} \rightarrow -i \vec{\nabla}$



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



became known (later) as the  
"Klein-Gordon equation"

$$\square^2 \psi + m^2 \psi + V(r) \psi = 0$$

but ... it describes particles that can 'disappear'



Paul A.M. Dirac  
(1928)

# One more try (still $\hbar c = 1, V = 0$ )

relativistic

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



square-root

$$\pm \sqrt{E^2} = p^2 + m^2$$



$$\gamma_0 E = \gamma_1 p_1 + \gamma_2 p_2 + \gamma_3 p_3 + m \quad *$$

$$i\gamma_0 \frac{\partial}{\partial t} \psi = -i\vec{\gamma}_{(1,2,3)} \frac{\partial}{\partial \mathbf{x}_{(1,2,3)}} \psi + m\psi$$

“Dirac equation”

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

time and space coordinates  
treated equally!  
time and space coordinates  
treated equally!



have to be 4x4 matrices

# RELATIVISTIC ELECTRON WAVE FUNCTION

$$\Psi = \left( \begin{array}{c} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{array} \right) \begin{array}{l} \text{Electron, spin up} \\ \text{Electron, spin down} \\ \text{Positron, spin up} \\ \text{Positron, spin down} \end{array}$$

ELECTRON **SPIN 1/2** EXPLAINED

**ANTIPARTICLES** MUST EXIST !

**SPIN 1/2 PARTICLES (FERMIONS): (PAULI) EXCLUSION PRINCIPLE**

END OF INTERLUDE 2

# ANTIPARTICLES



Anderson

1932: POSITRON DISCOVERY



EVERY PARTICLE HAS AN ANTIPARTICLE

$$E=mc^2$$



WHEN ENERGY CONVERTS TO MASS,  
PARTICLES AND ANTIPARTICLES ARE PRODUCED

# QUANTUM FIELD THEORY (1927 - 1948)



S.I. Tomonaga

Since the classical electromagnetic field consists of photons - how should the interaction between electrons and photons be correctly described, based on the principles of special relativity and quantum physics?



J. Schwinger

Second quantization:

Particles are treated as excitations of an underlying field  
Creation and annihilation operators



F. Dyson

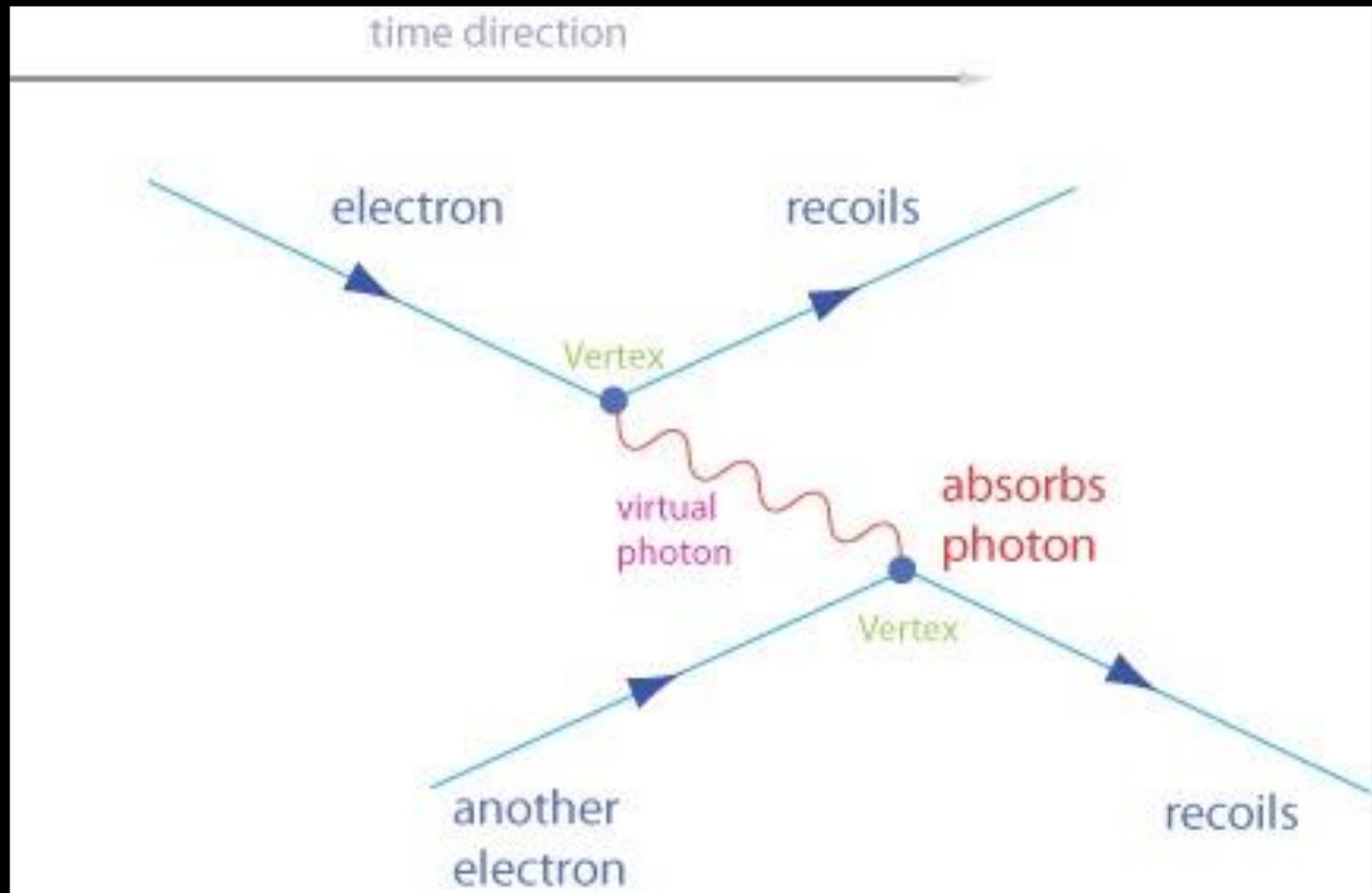
# QUANTUM ELECTRODYNAMICS (1948)

Feynman graphs:

Graphical notation of particle reactions in space-time to derive probability amplitudes



R.P. Feynman

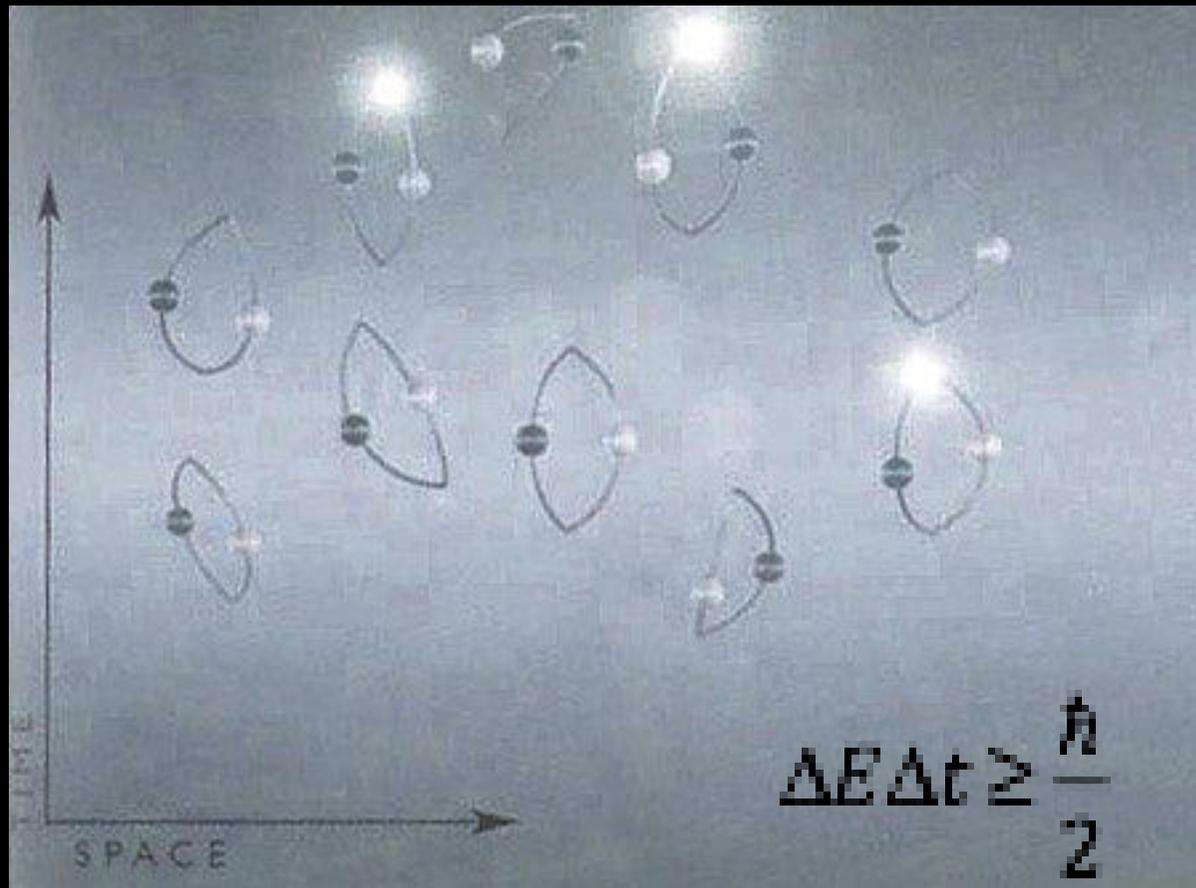


# VACUUM FLUCTUATIONS

Quantized fields: Ground state energy is  $\neq 0$

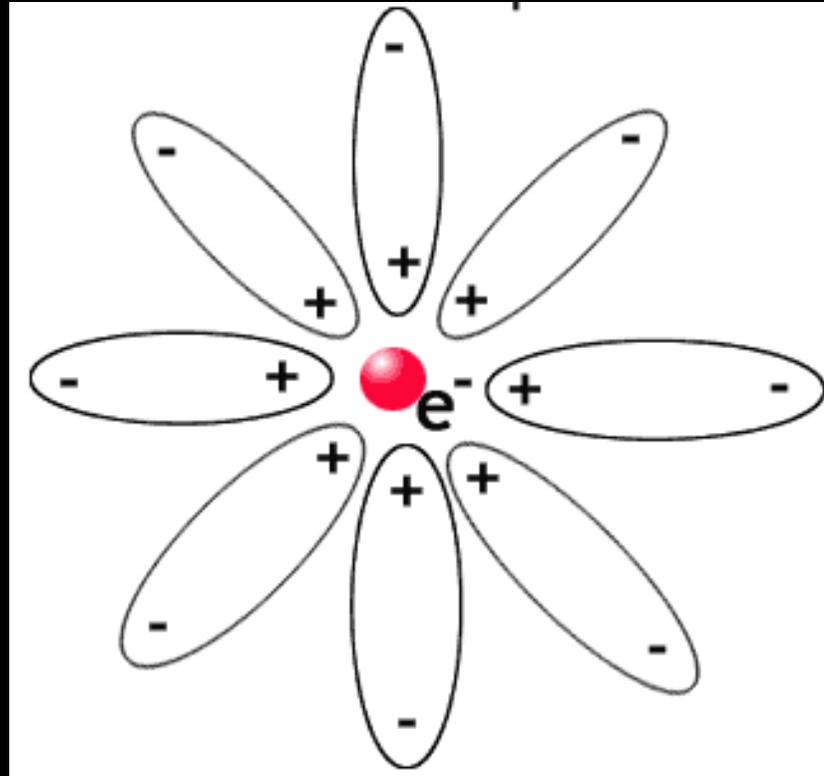
QF fluctuations and particle-antiparticle-pairs populate empty space !

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



# RENORMALISATION

The 'naked' electron + vacuum fluctuations = electron

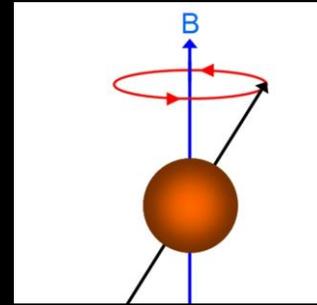


Vacuum fluctuations: charge (hence coupling constant) are energy dependent

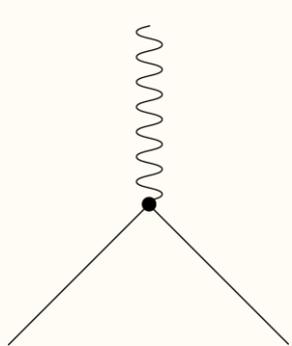
# BEST THEORETICAL PREDICTION EVER

*Vacuum fluctuations have observable effects*

*Electron anomalous magnetic moment "g"*

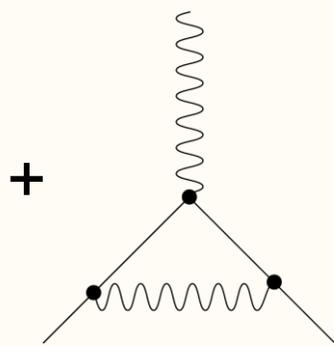


$$\mu = g \frac{e}{2m} S$$



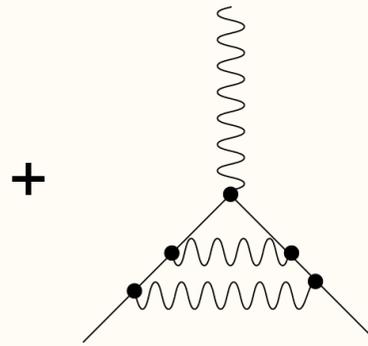
"Leading order"

$$g = 2$$

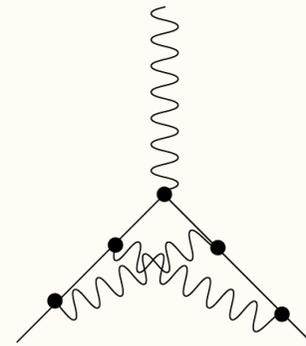
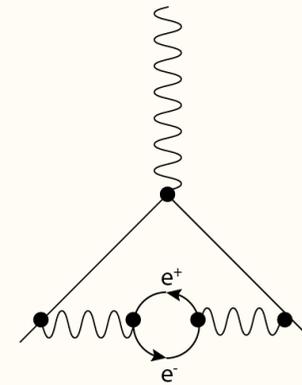


Second order

$$a = (g-2)/2 = 1/2\pi * 1/137$$
$$\sim 0.0011614$$

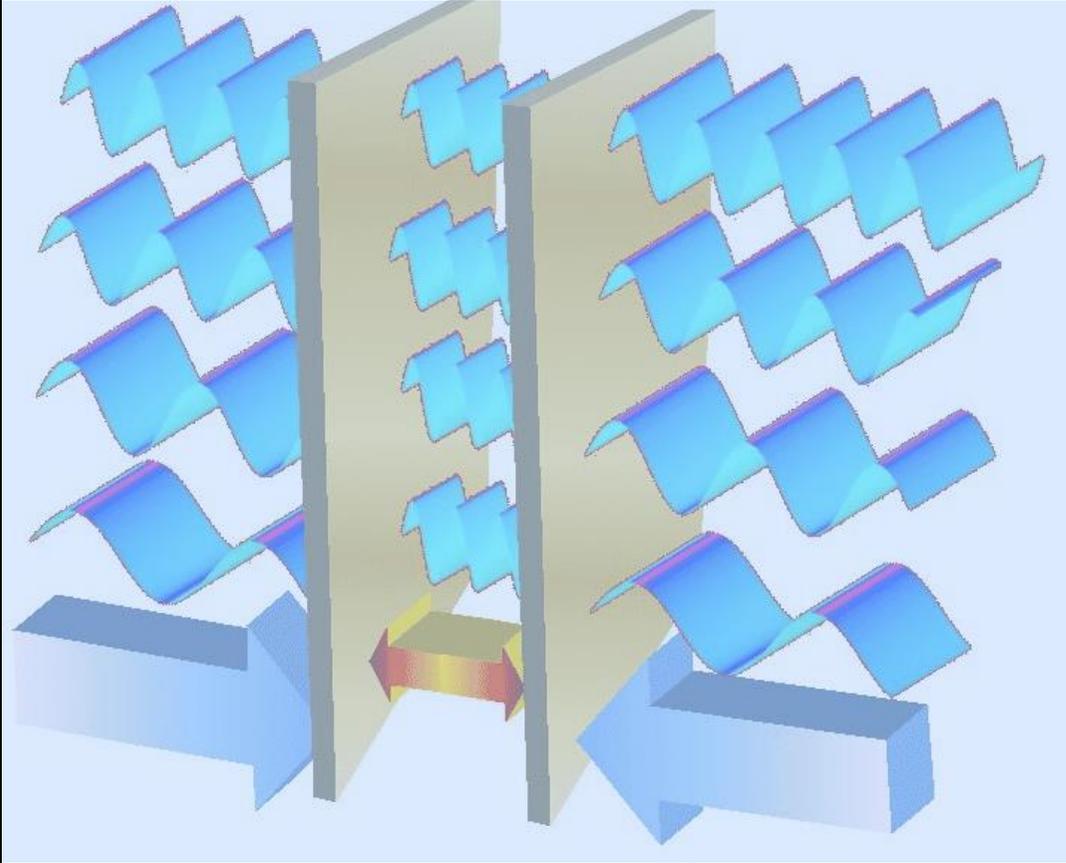


Fourth order corrections



*Current precision (theory and experiment agree.)*  
 $a = 0.00115965218073(28)$

## CASIMIR EFFECT



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

$$p = 100 \text{ kPa (d=11 nm)}$$

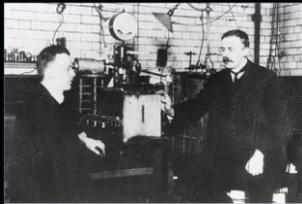
SPOOKY: at 11 nm distance, the pressure is 1 atm.

# "NUCLEAR" PHYSICS



M. Curie

1895-1900: **RADIOACTIVITY** - strange radiation phenomena



E. Rutherford

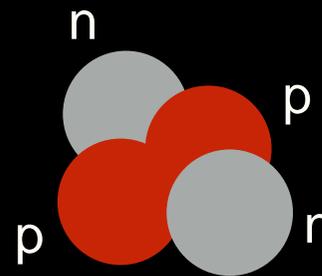
1903: Alpha-, Beta-, Gamma-Radiation

1911: **Nucleus** - positive, very small - surrounded by electrons



J. Chadwick

1932: **NEUTRON**

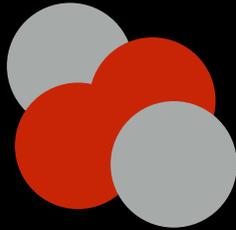


Alpha particle = He nucleus

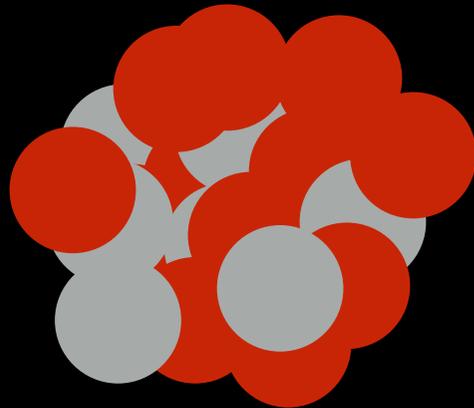
# NUCLEAR PHYSICS - 1934



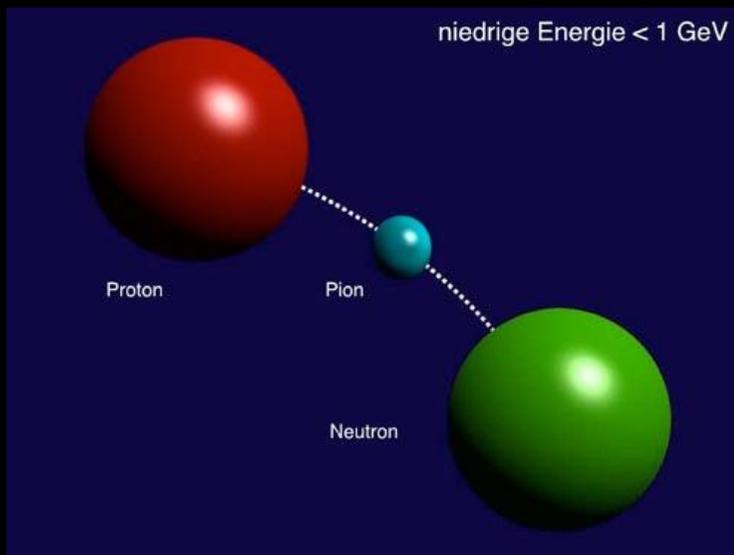
Yukawa (1934)



What keeps protons and neutrons together ?

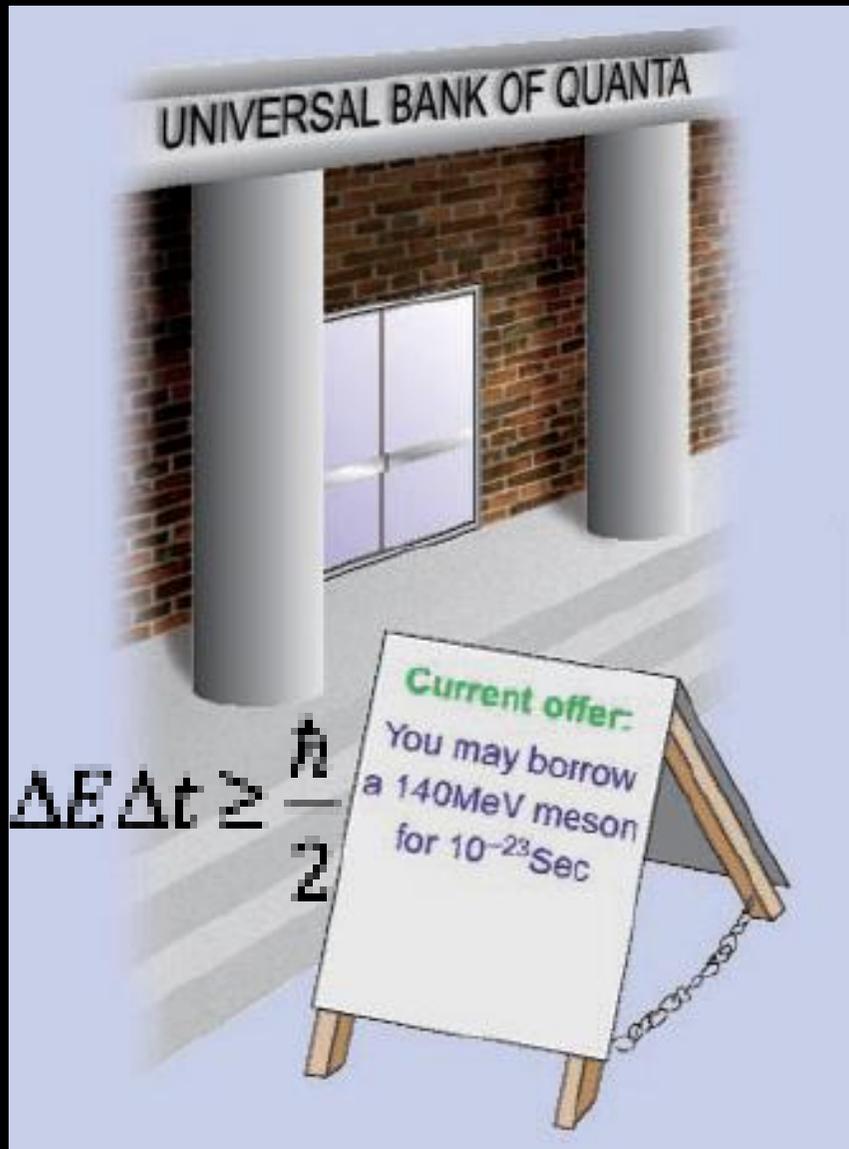


Why is the range of nuclear forces finite?  
(maximum size of nuclei  $\sim 5$  fm)



Yukawa model:

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

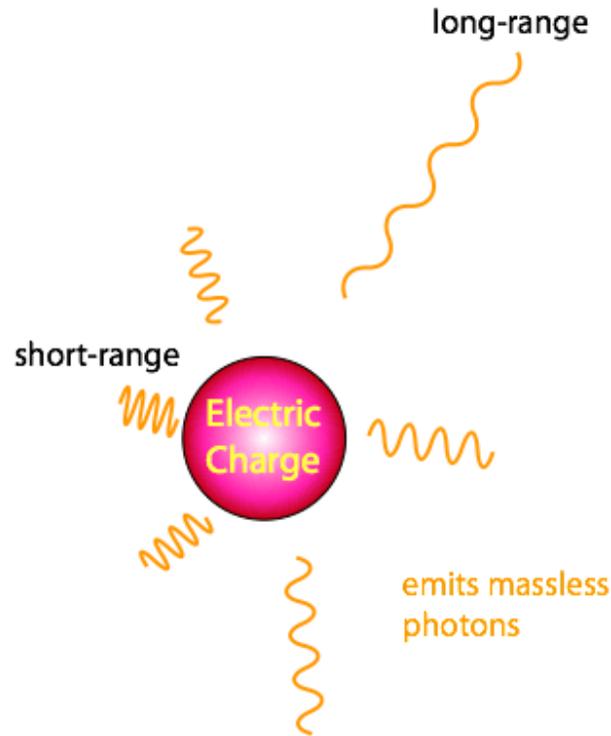


Toy model:

UBS offers you a loan of

**1000 Euro x Seconds**

# Electromagnetic vs Nuclear Exchange Forces



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

Coulomb law



emits massive pions

$$\Delta E \Delta t \geq \hbar \quad (\Delta E \sim m)$$

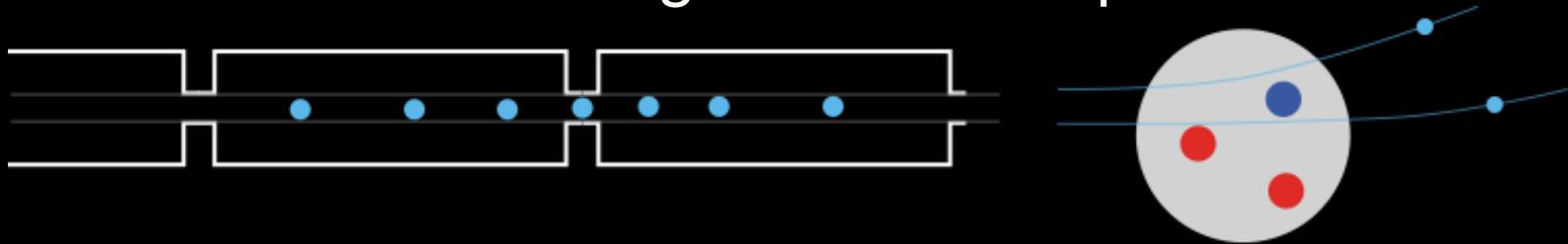
$$r = c \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

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

Yukawa potential  $\sim$  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** contained  $\sim 200$  'elementary particles'

$\pi^+$   $\pi^-$   $\pi^0$

Pions

$K^+$   $K^-$   $K^0$

Kaons

$\eta'$

Eta-Prime

$\eta$

Eta

$\phi$

Phi

$\rho^+$   $\rho^-$   $\rho^0$

Rho

**Mesons**

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

Delta

$\Lambda^0$

Lambda (strange!)

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

Sigma (strange!)

$\Xi^0$ ,  $\Xi^-$

Sigma(very strange!)

**BARYONS**

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

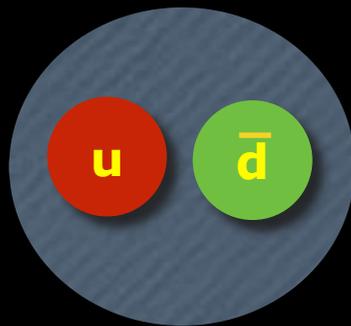


-1/3



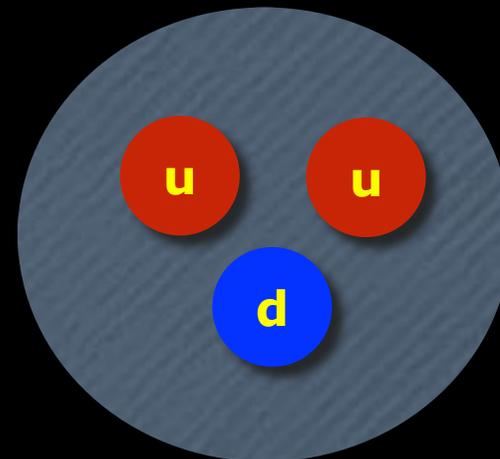
-1/3

electric charge



$\pi^+$

Meson



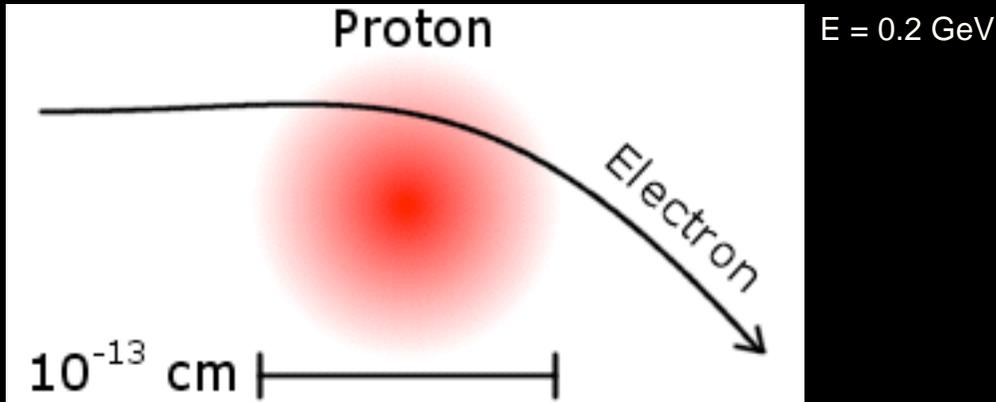
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Baryon

# Discovery of quarks

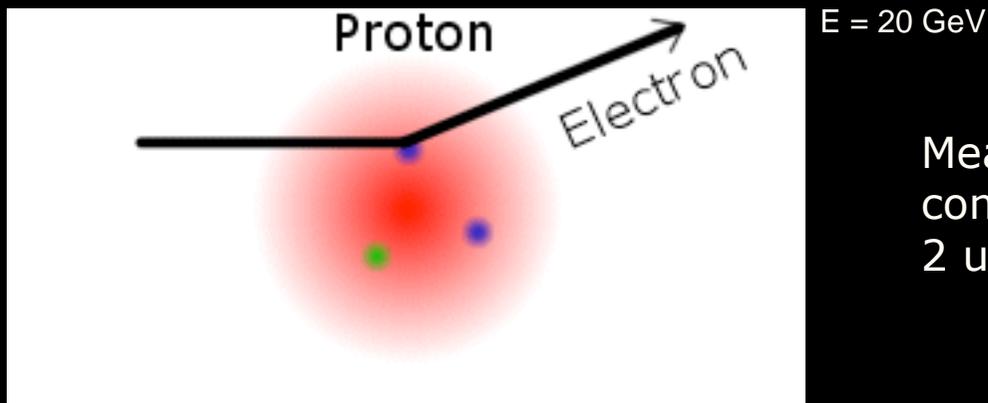
Electron-Proton scattering at Stanford

1956 Hofstadter: proton radius  $\sim 1$  fm



*Stanford Linear Accelerator Centre*

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



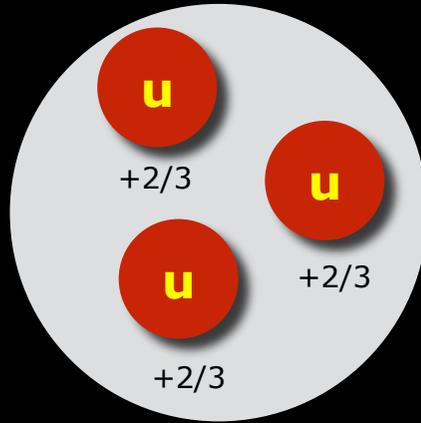
Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

# The concept of "Colour" charge

How can you explain this particle ?

$\Delta^{+++}$

Spin =  $3/2$



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

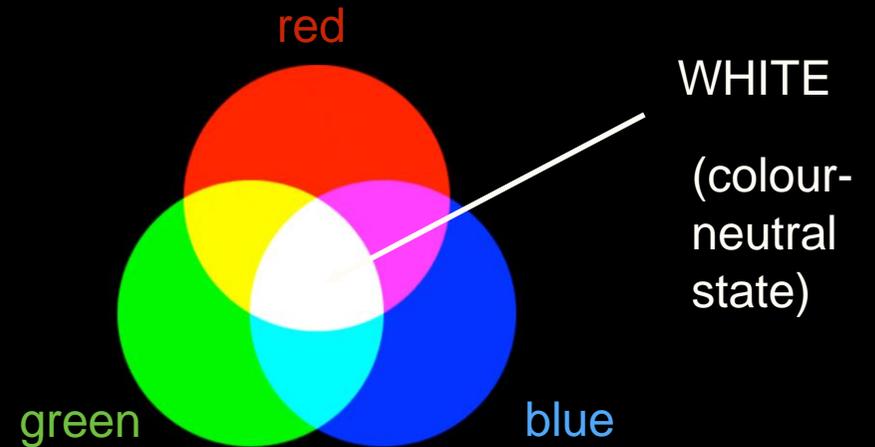
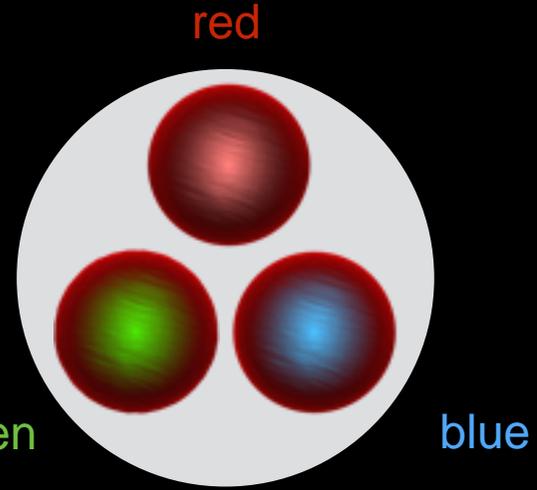
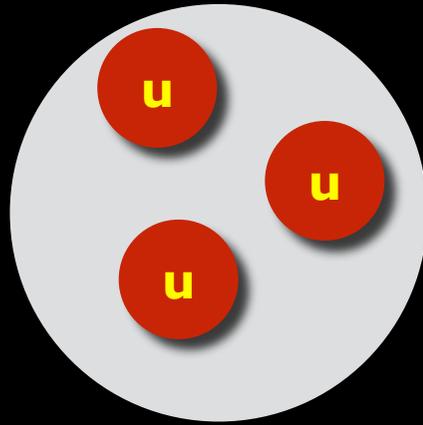
**A new concept: "colour charge"**

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

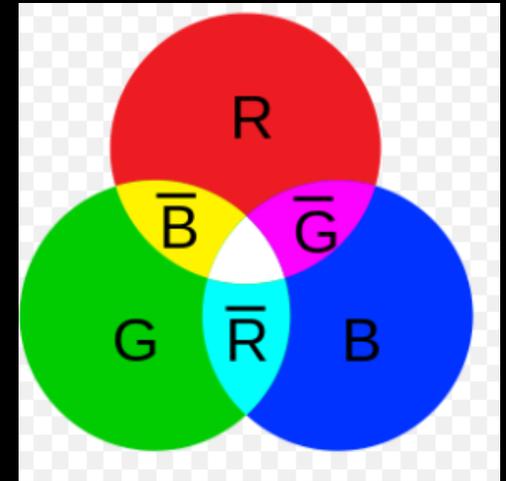
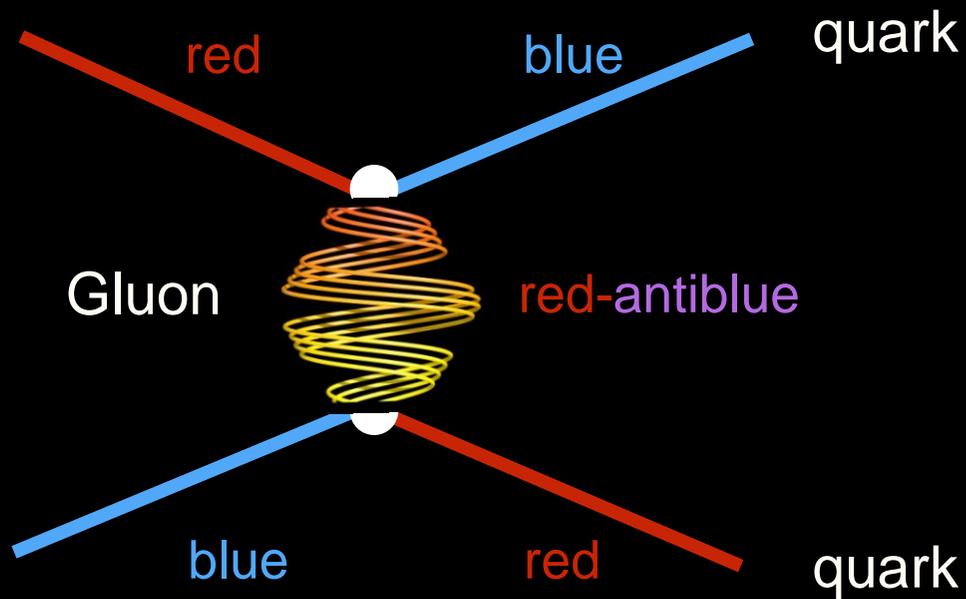
(Bardeen, Fritzsche, Gell-Mann)

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

$\Delta^{+++}$



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

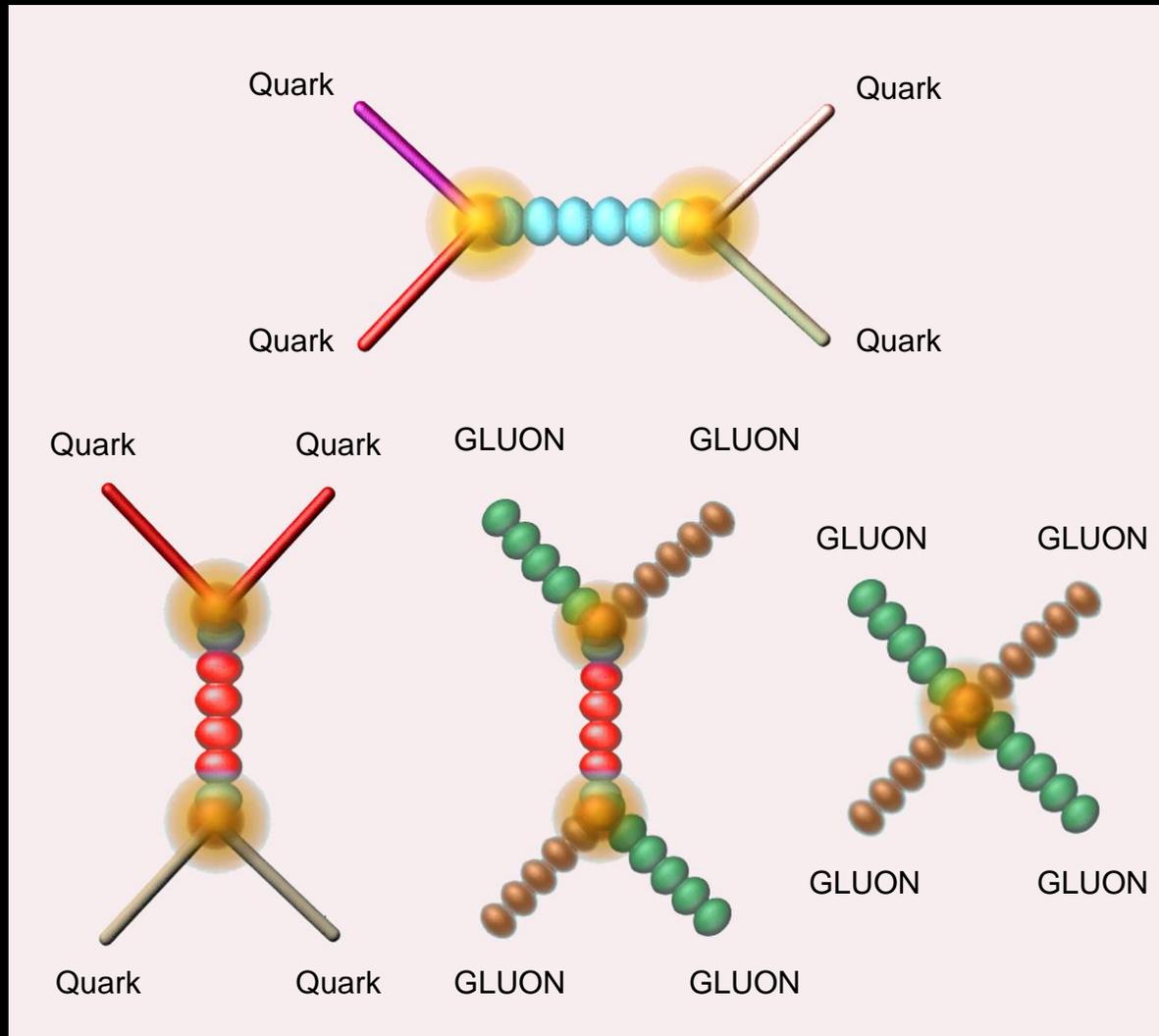


Total number of gluons:  $3 \times 3 - 1 = 8$

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

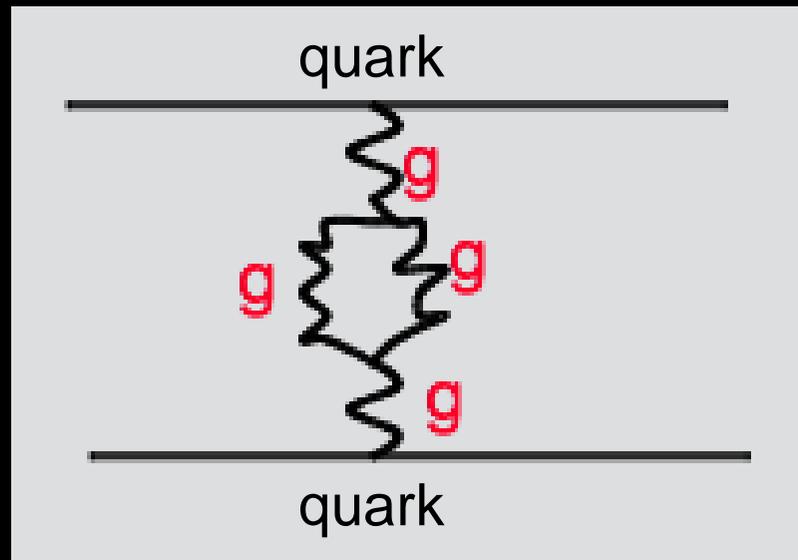
Since gluons carry a (colour) charge:

Gluons can interact with other gluons

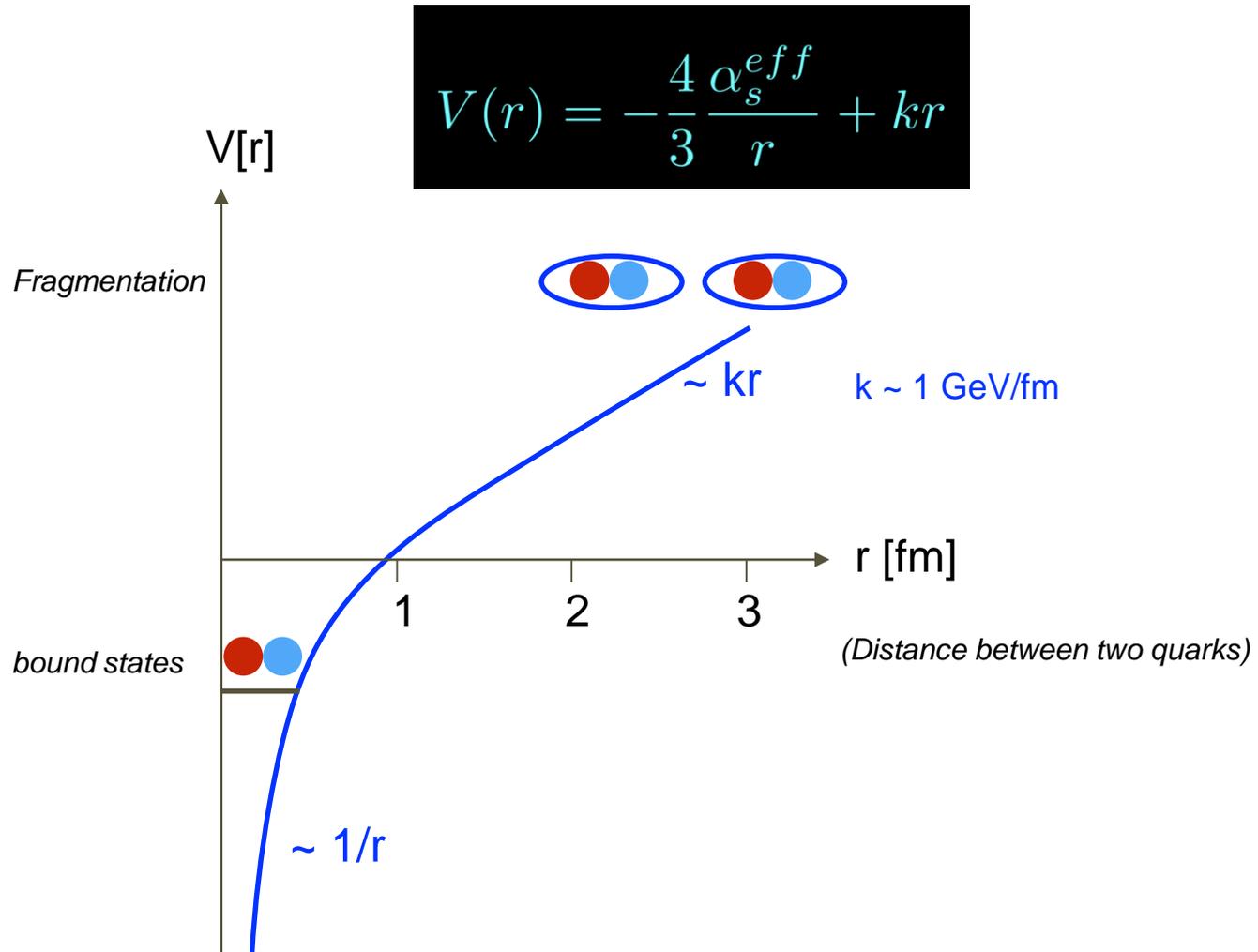


The self-interaction of the gluons results in the energy of the gluon string increasing with distance between quarks.

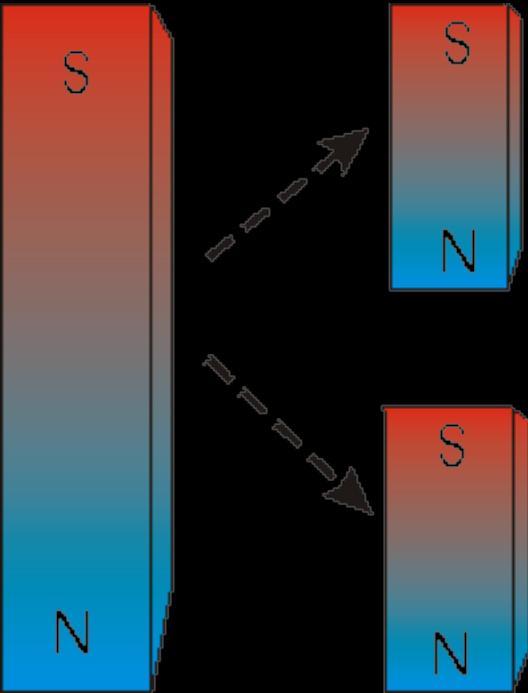
This produces a force that keeps the quarks as 'prisoners'.



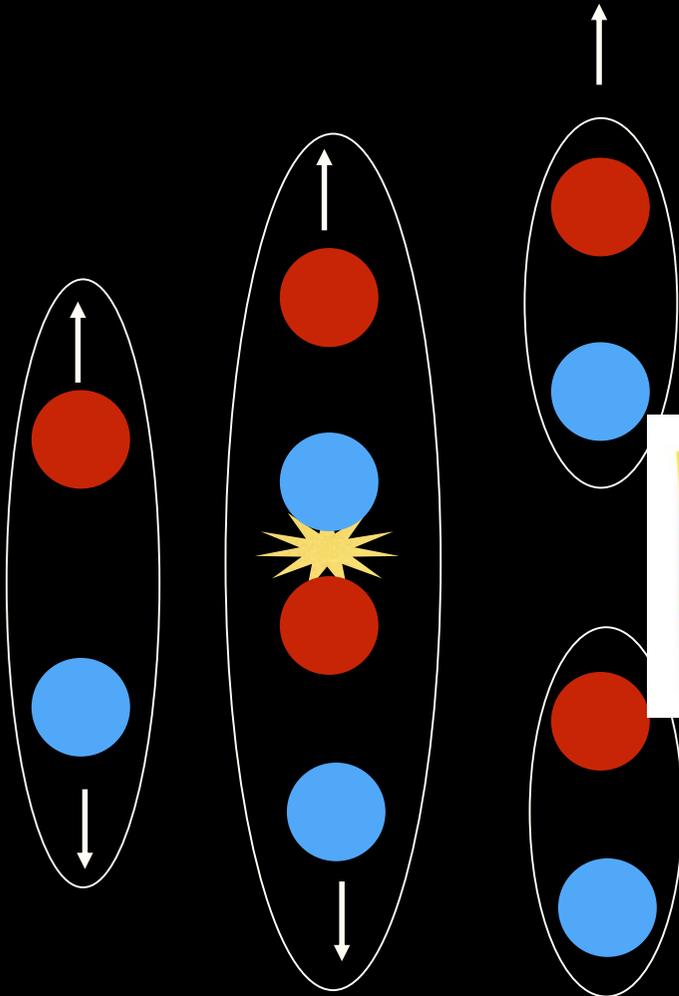
# QCD 'potential' between two quarks



# 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

