

PARTICLE PHYSICS AND COSMOLOGY

in the 20th century

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DISCLAIMER

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

More than 50 Nobel prize winners on particle physics

Very difficult to be comprehensive, exact or in-depth

This is a broad overview about the main discoveries.

All that remains to do in physics is to fill in
the sixth decimal place

(Albert Michelson, 1894)

Kinetic theory,
Thermodynamics

Boltzmann

Maxwell

Newton

Particles

Fields

Universe

Technologies

Electromagnetic Weak Strong

Detector

Accelerator

1895

e^-

Brownian motion

Photon

Radio-activity

1900

Atom

1905

Nucleus

Special relativity

1910

p^+

Quantum mechanics
Wave / particle
Fermions / Bosons

1920

n

Spin
Antimatter

1930

e^+

Fermi Beta-Decay

Yukawa
 π exchange

Galaxies; expanding universe

Cyclotron

1940

μ^-

Dark Matter

Nuclear fusion

1950

τ^-

π
Particle zoo

QED

P, C, CP violation

Big Bang Nucleosynthesis

Bubble Chamber

Synchrotron

1960

ν_e

p

Higgs

W bosons

Cosmic Microwave Background

Wire chamber

e^+e^- collider

1970

ν_μ

u d s

GUT

EW unification

QCD Colour

Online computers

Beam cooling

1975

τ^-

c

STANDARD MODEL

SUSY

Inflation

Modern detectors

p^+p^- collider

1980

ν_τ

b

Superstrings

W

Z

g

CMB Inhomogeneities (COBE, WMAP)

WWW

1990

t

3 generations

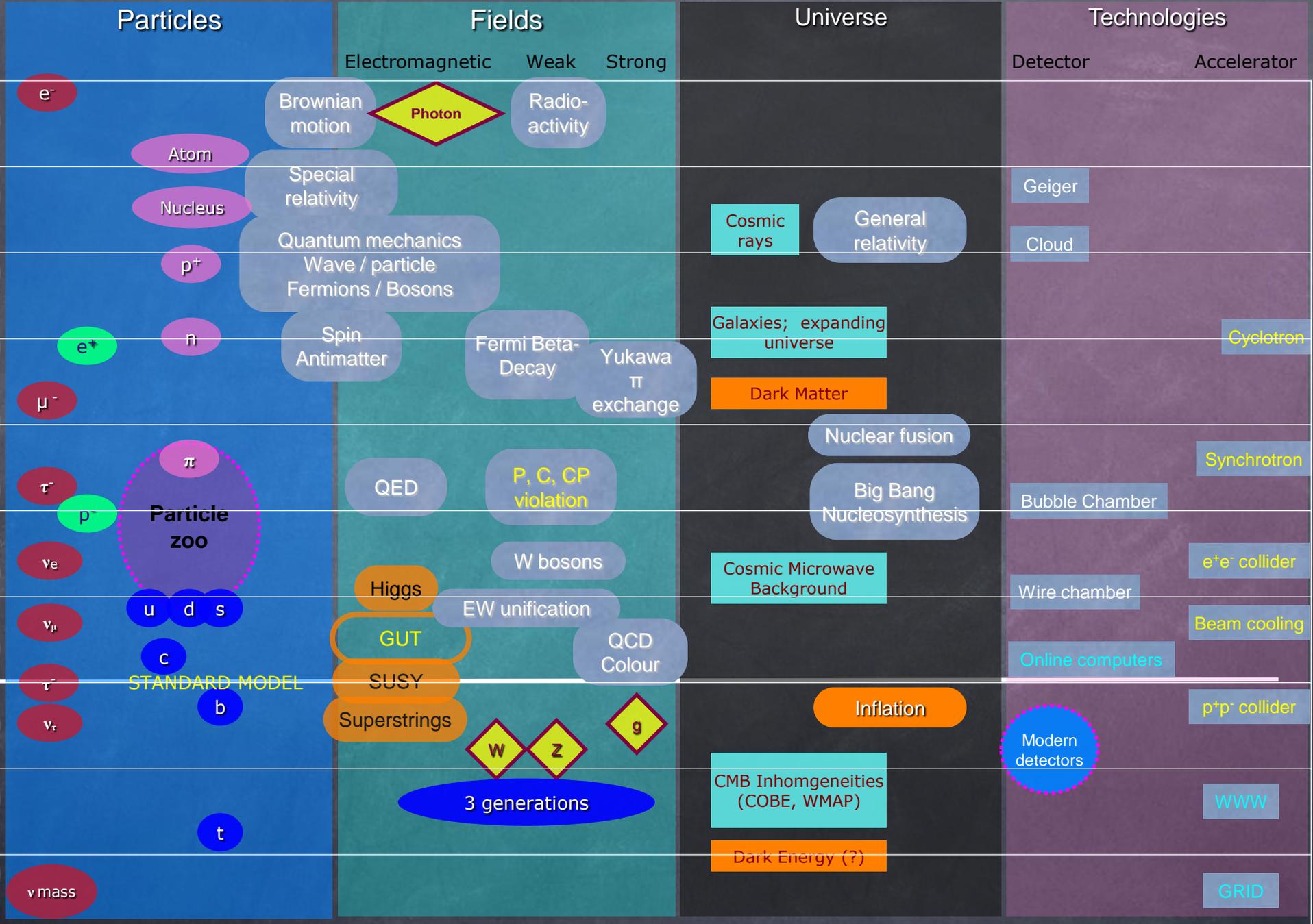
2000

ν mass

Dark Energy (?)

GRID

2010



Kinetic theory,
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1895

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1905

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1940

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1960

1970

1975

1980

1990

2000

2010

1

e^-

Atom

Nucleus

p^+

n

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Brownian motion

Special relativity

Quantum mechanics

Wave / particle

Fermions / Bosons

Spin

Antimatter

2

QED

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Cosmic rays

Galaxies; expanding universe

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Geiger

Cloud

Cyclotron

Synchrotron

Bubble Chamber

μ^-

τ^-

ρ^-

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CMB Inhomogeneities (COBE, WMAP)

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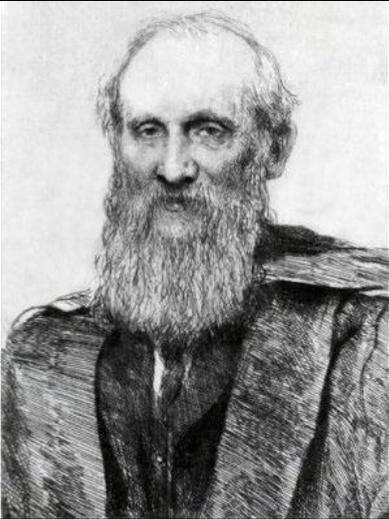
ν mass

Dark Energy (?)

Dark Energy (?)

GRID

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



**William Thomson
(Lord Kelvin)**

Address to the British Association for the
Advancement of Science, 1900

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

But Lord Kelvin also mentioned two 'clouds' on
the horizon of physics:

- 1) Blackbody radiation
- 2) Michelson-Morley experiment

1900

Universe = solar system and the stars of our galaxy

Nobody knew how the sun produced its energy

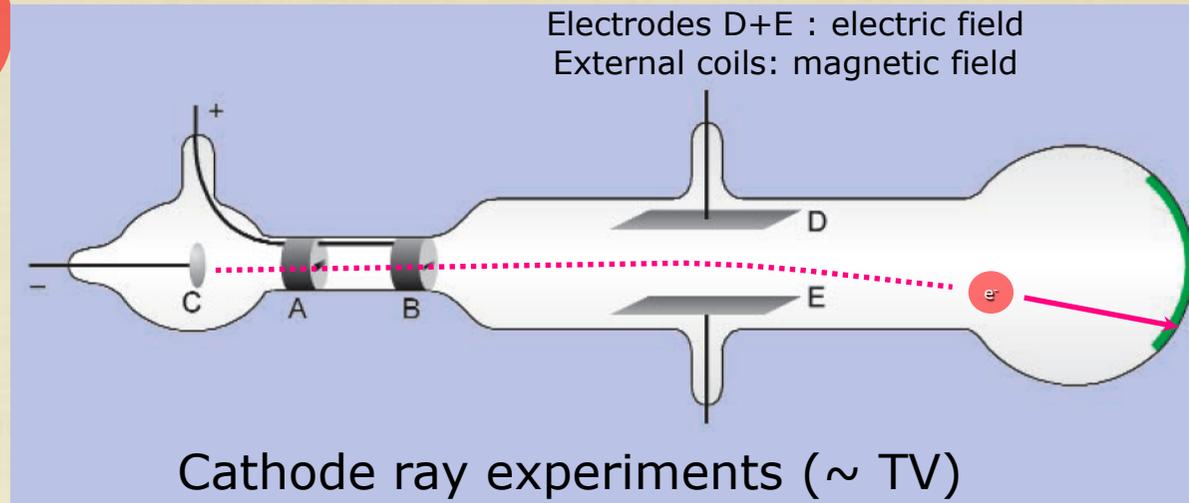
Nothing was known the structure of atoms and nuclei

Only two known fields: gravitation, electromagnetism

Nobody anticipated the incredible journey of physics in the next 100 years



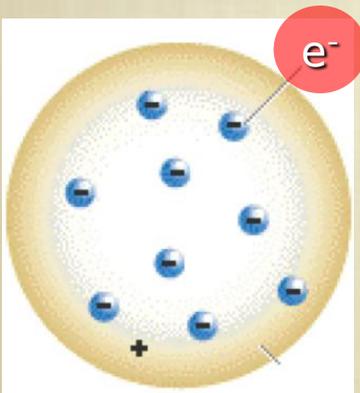
J.J. Thomson

 e^-


**'Rays' are charged corpuscles*
with unique charge/mass ratio**

***later called 'electrons'**

Electrons are sub-atomic particles!



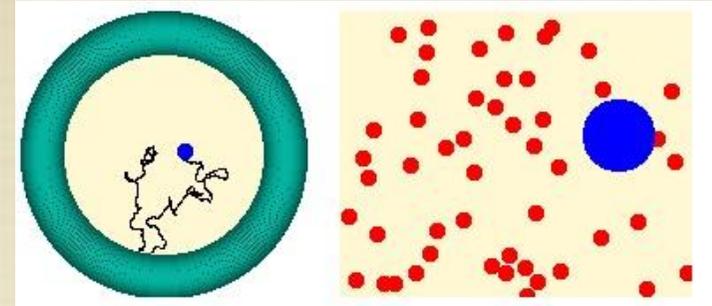
His 'plum pudding' model
of the atom (1904)

Robert Brown (1827) observes random walk of small particles suspended in a fluid



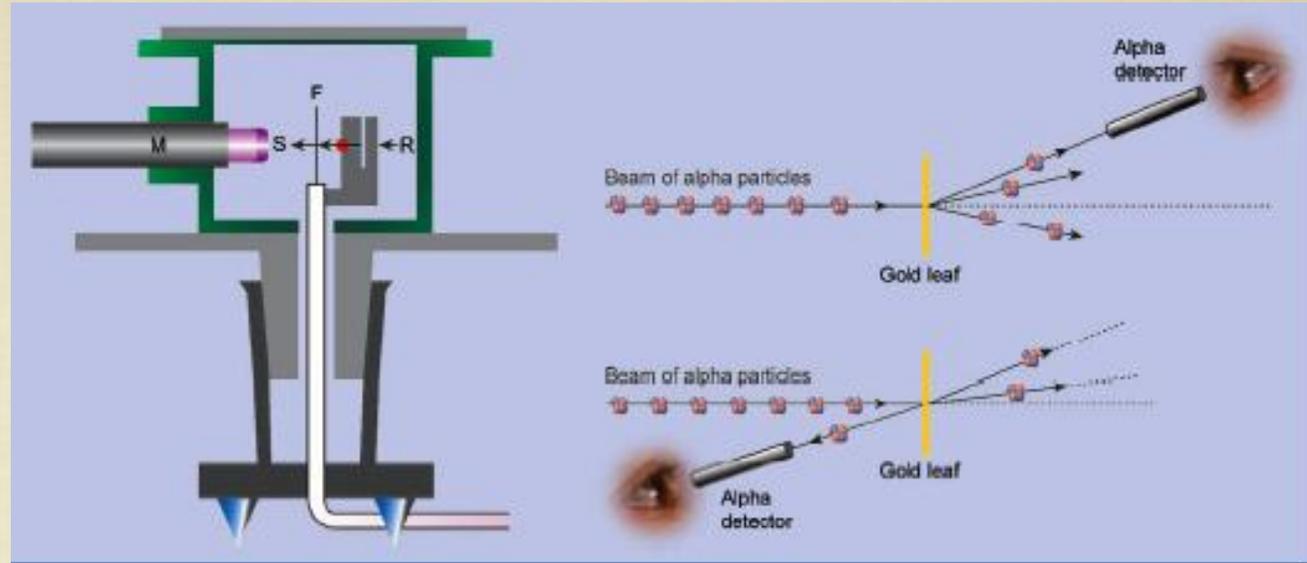
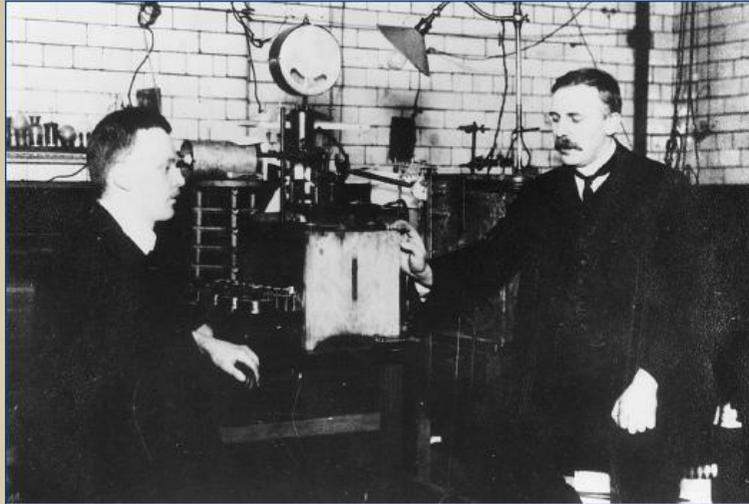
Albert Einstein (1905) explains by kinetic theory that the motion is due to the bombardment by molecules

Francois Perrin (1907) uses Einstein's formula to confirm the theory and measure Avogadro's number



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

The existence of atoms was proven



Ernest Rutherford (r) and Hans Geiger (l)
in Manchester

Geiger and Marsden fired alpha particles (He nuclei) on gold foils
1 in 8000 alpha particles were backscattered ($> 90^\circ$)

This could not be explained by the 'plum pudding model'

Rutherford's explanation: all the mass of the atom is concentrated in the nucleus

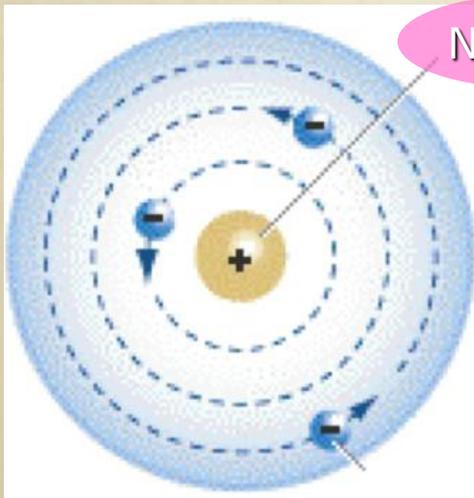
Size: At minimum distance, Coulomb repulsion = kinetic energy: $\sim 27 \times 10^{-15} \text{ m}$ (true value: 7.3)

Discovery of the nucleus

Analogy with solar system:

If the nucleus had the size of the Sun

the electrons would orbit in 1000 x the distance of Sun-Earth



? **How can electrons orbit a nucleus without radiating their energy?**

? **What is the nucleus made of ?**

Rutherford's model
of the "empty" atom

PARTICLE SPECTRUM

1923-1927

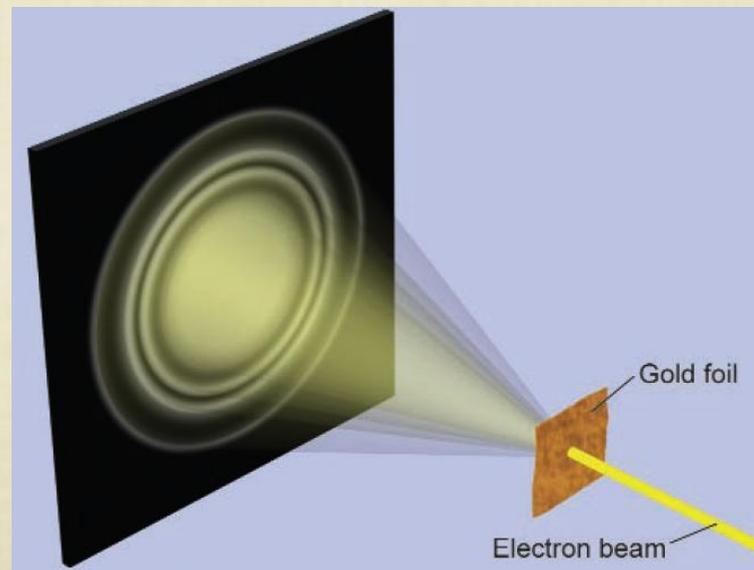
It took 10 more years to understand the mysterious rules governing the atomic world: quantum mechanics.



Louis de Broglie (1924)

Particles behave like waves

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



*this hypothesis was confirmed in 1927 by electron diffraction (Davisson/Germer)



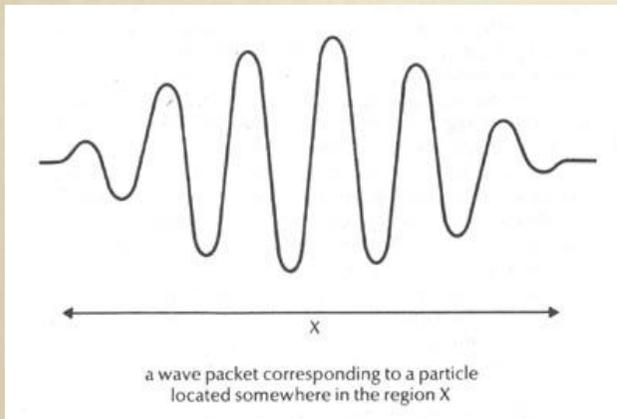
Uncertainty relation

If particles are waves (of finite size), then there must be a limit to the precision of measurement between:

Heisenberg (1925)

Position and momentum

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



Analogy:

Measurement time Δt of a signal leads to uncertainty of frequency (Fourier transform):

$$\Delta f \Delta t \sim 1$$

Energy and time

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

Probability wave function

Excellent description
if $v \ll c$

If particles are waves -> describe by a wave equation

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



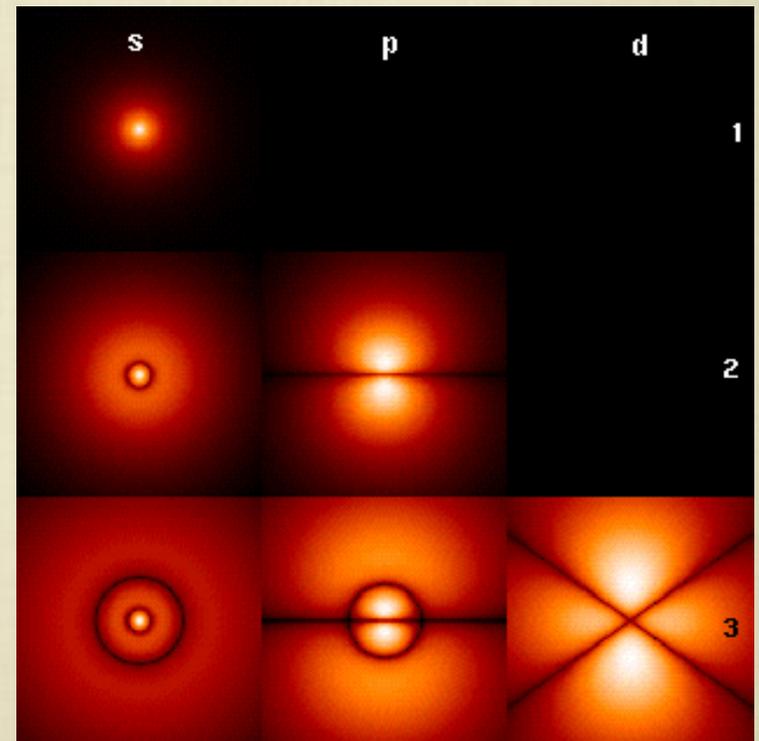
Schrödinger
1926

Interference: ψ = complex function

Interpretation (Born, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability



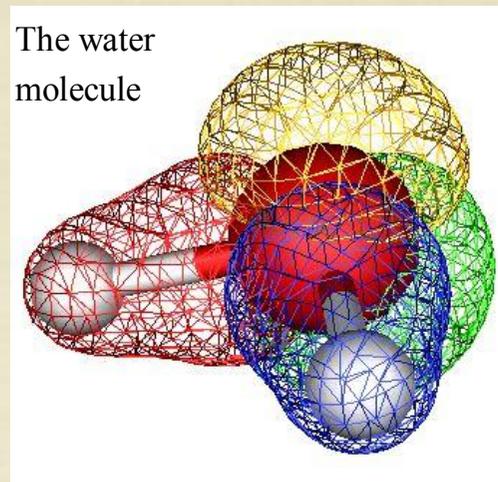
Electron wave functions in hydrogen atom
(‘standing 3-dim waves’)

Quantum physics explained the existence of 'structure' in nature



Linus Pauling (1928)

The nature of chemical bonds



Atoms, Molecules and the origin of structure were understood.

And the atomic nucleus? Not much progress between 1911 - 1932.

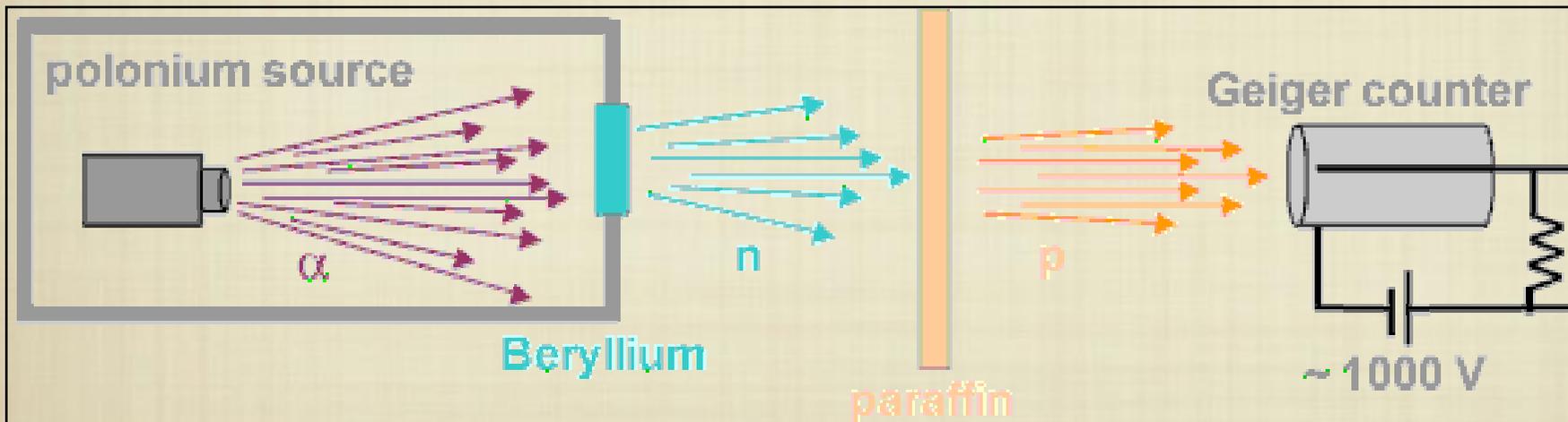
What is the nucleus made of ?

For example: He-4 has only $Z=2$; what are the other two units of mass due to ?

Heisenberg: Protons and electrons (4 protons and 2 electrons)?

Did not work - the uncertainty relation forbids the presence of electrons in the nucleus!

Chadwick (1932): The neutron

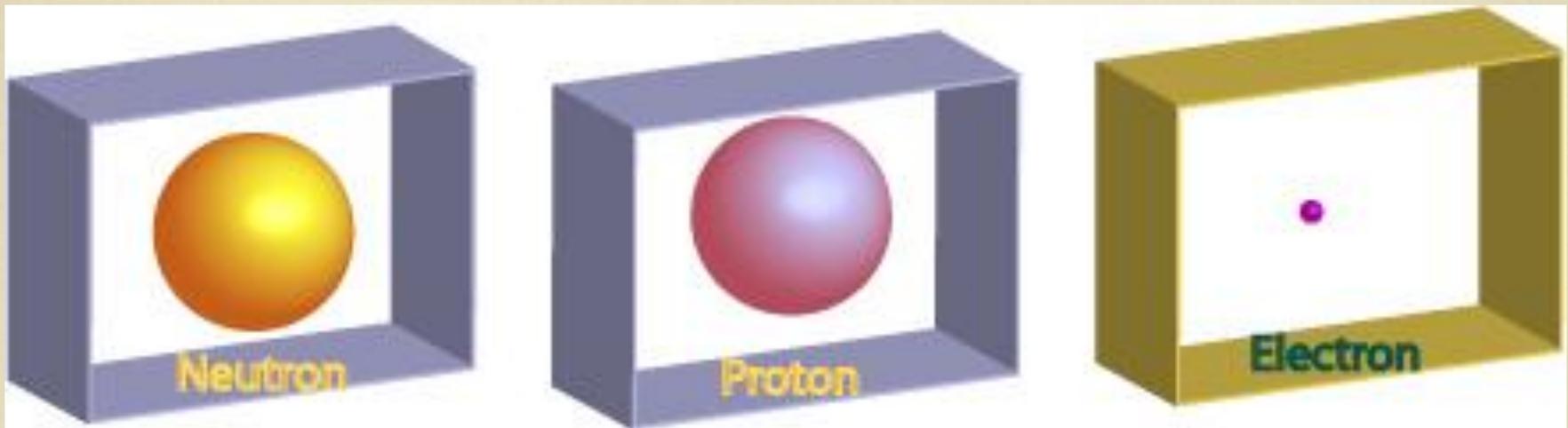


From kinematics: Mass of neutron \sim mass of proton

What keeps everything together? Strong short-range interaction?

PARTICLE SPECTRUM

Fundamental particle spectrum (1932)



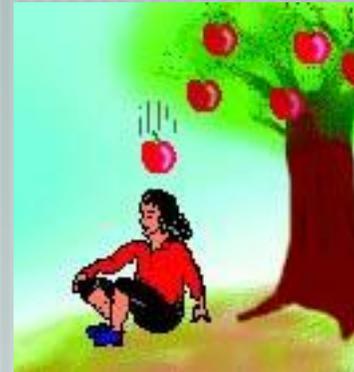
**Simple, easy to remember
Still taught at schools
(usually in chemistry lessons)**

What holds atoms and nuclei together?

1900: two fundamental interactions were known:

$$F_G = G m_1 m_2 \cdot \frac{1}{r^2}$$

$$F_C = Q_1 Q_2 \cdot \frac{1}{r^2}$$



Gravitation

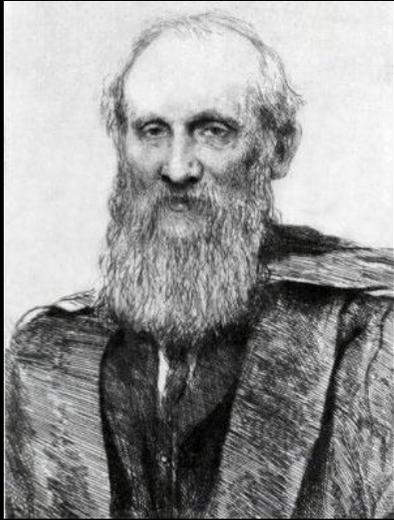


Electromagnetism

Similarities: both have inverse square dependence on radius

Differences: the strength of the forces is vastly different (38 orders of magnitude!)

Remember: in 1900, there were two 'clouds' on the horizon of physics:



**William Thomson
(Lord Kelvin)**

Two clouds:

- 1) Blackbody radiation**
- 2) Michelson-Morley experiment**

Their understanding would lead to

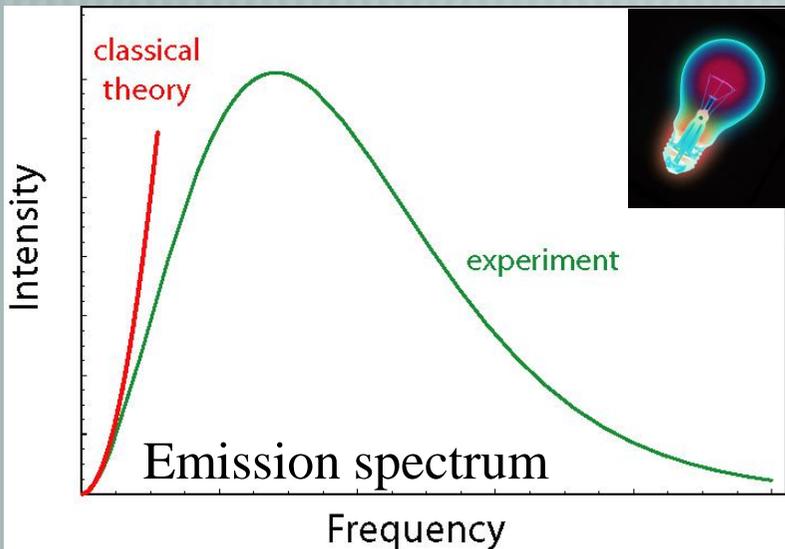
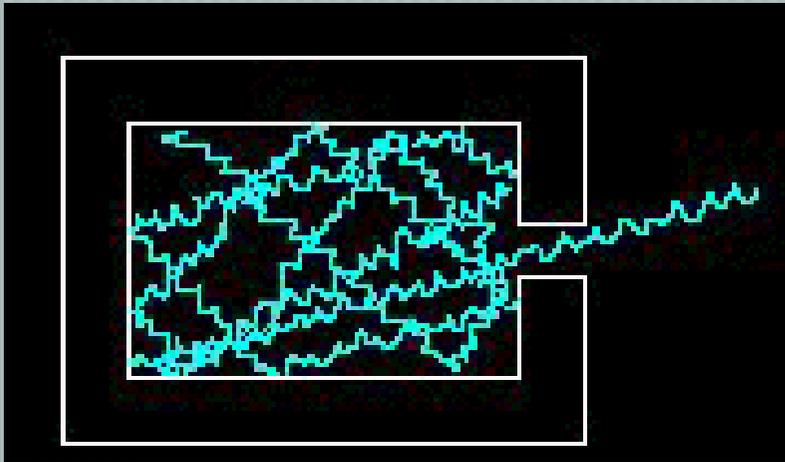
- quantum theory**
- relativity**

Fields

'Electromagnetic' interaction

Photon

Blackbody radiation



"Black body" absorbs all incoming light; re-emits thermal equilibrium radiation

"Radiation function" = $f(T)$ only

$$I(\nu) \sim \nu^2 \langle E \rangle$$

average energy of oscillators
(proportional to temperature)

Ok for 'low' temperatures (Jeans law)

Fields

'Electromagnetic' interaction

Photon

An "Act of Desperation"

Oscillators (in the wall of the black body)
emit 'finite energy elements' $\epsilon = h\nu$

14 December 1900

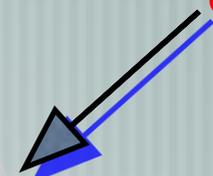


Max Planck

Higher frequency means bigger chunks, so it is less likely to find $E \gg kT$

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

average energy
of oscillators



h = new fundamental constant

Fields

'Electromagnetic' interaction

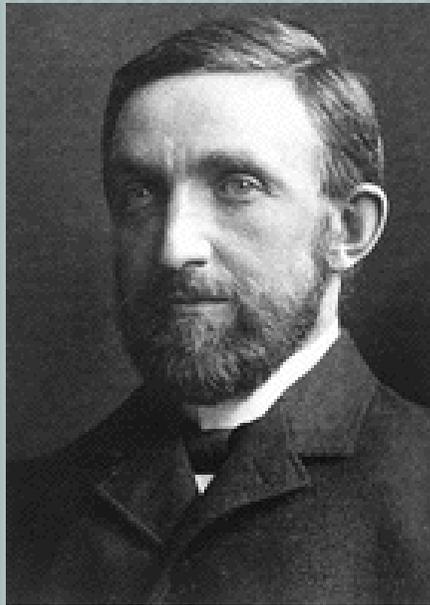
Photon

1902

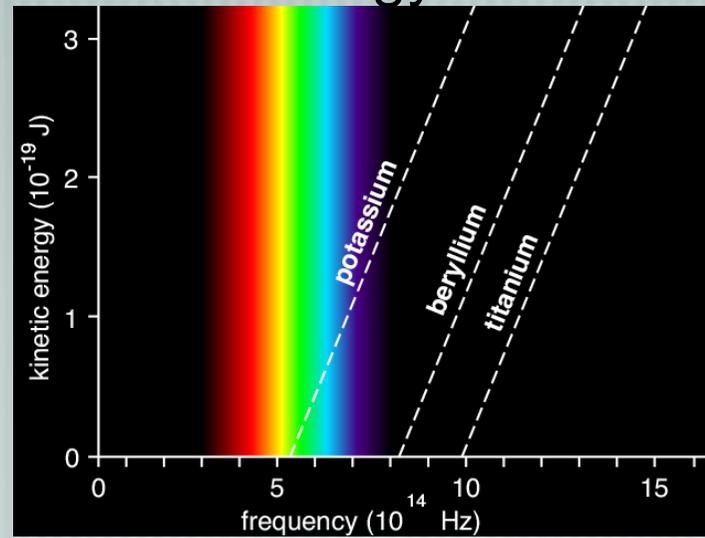
The photoelectric effect

Cathode rays (electrons) are produced by shining light on metal surfaces.

Classical expectation: Energy of light proportional to square of its amplitude ~ electron energy



Philipp von Lenard



Energy proportional to light **frequency** (slope = "h")

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

Fields

'Electromagnetic' interaction

Photon

“My only revolutionary contribution”

17 March 1905



Albert Einstein

Light is emitted and **absorbed** in **quanta**

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

“A *light quantum* gives all its energy to a *single electron*.”

Photons are particles.

(Compton, 1917, proved it)

Special relativity

Einstein had thought about the 'medium' for electromagnetic waves and concluded that there was none.

But how could the speed of light be the same in all inertial frames?

His postulates:

- 1) Speed of light = constant = c (in vacuum)**
- 2) all inertial frames are equivalent ("relativity principle")**

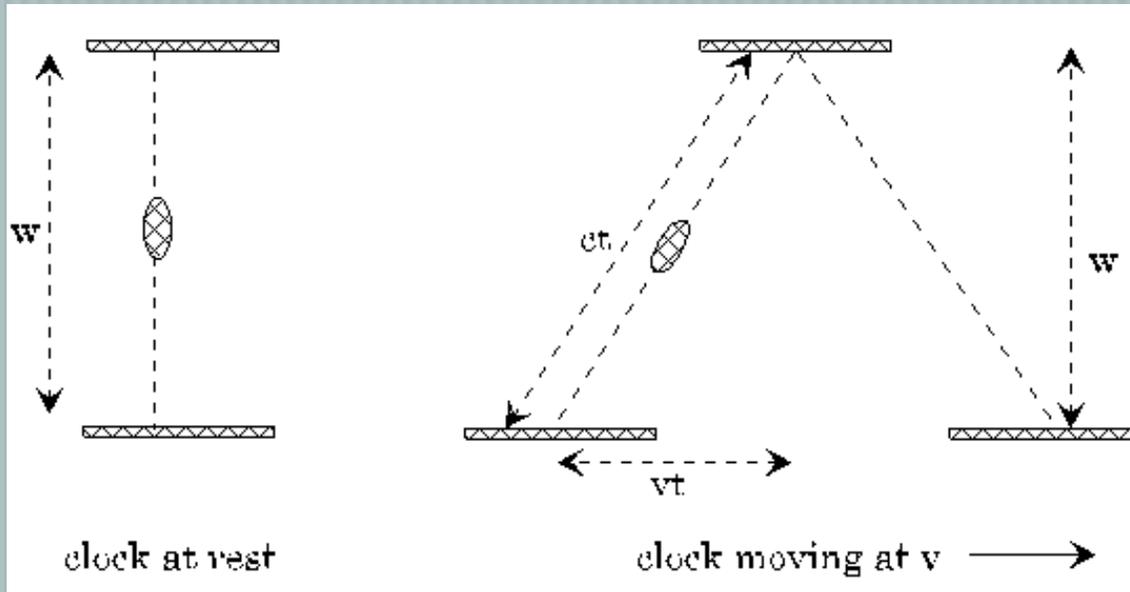
His conclusions:

Since $c = \text{constant}$ and $\text{speed} = (\text{space interval}/\text{time interval}) \rightarrow$

space and time cannot be absolute!

Fields

Special relativity



t = time observed for moving frame
 τ = time in moving frame ($w=c \tau$)

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

$$t^2 (c^2 - v^2) = w^2$$

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

1) Time dilation, space contraction

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

$$E=mc^2$$

Fields

'Electromagnetic' interaction

How could special relativity and quantum physics be united ?



Paul A.M. Dirac
(1928)

$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha \cdot p) + \beta m$$

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

Spin

Antimatter

Compare with (non-relativistic)
Schrödinger equation

$$E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi$$

CONSEQUENCES:

ELECTRON SPIN EXPLAINED
ANTIPARTICLES MUST EXIST !

ELECTRONS OBEY 'PAULI PRINCIPLE' (1940) - FERMIONS

Fields

'Electromagnetic' interaction

Two crucial (theoretical) **predictions** by Dirac

**The wave function has 4 components (two spin 1/2 particles)
2 components for particle - and 2 components for antiparticle!**

Every particle has an antiparticle !



Fields

e^+

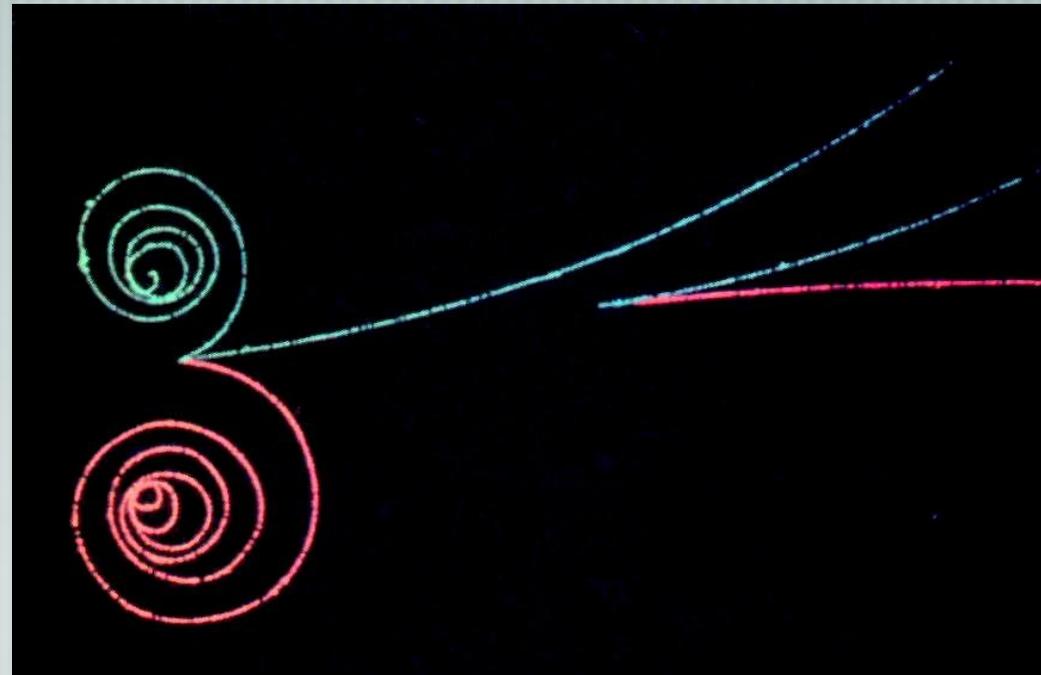
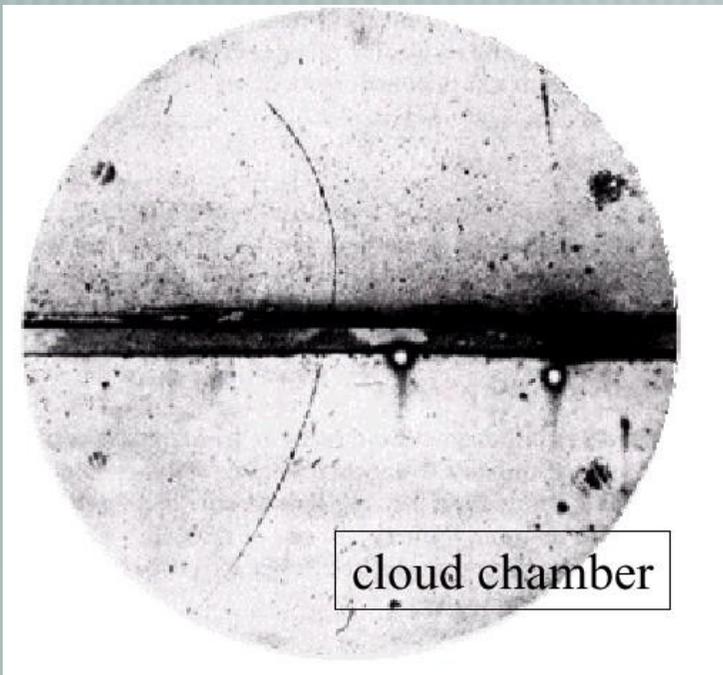
'Electromagnetic' interaction



Discovery of the positron

Dirac was right!

Anderson (1932)



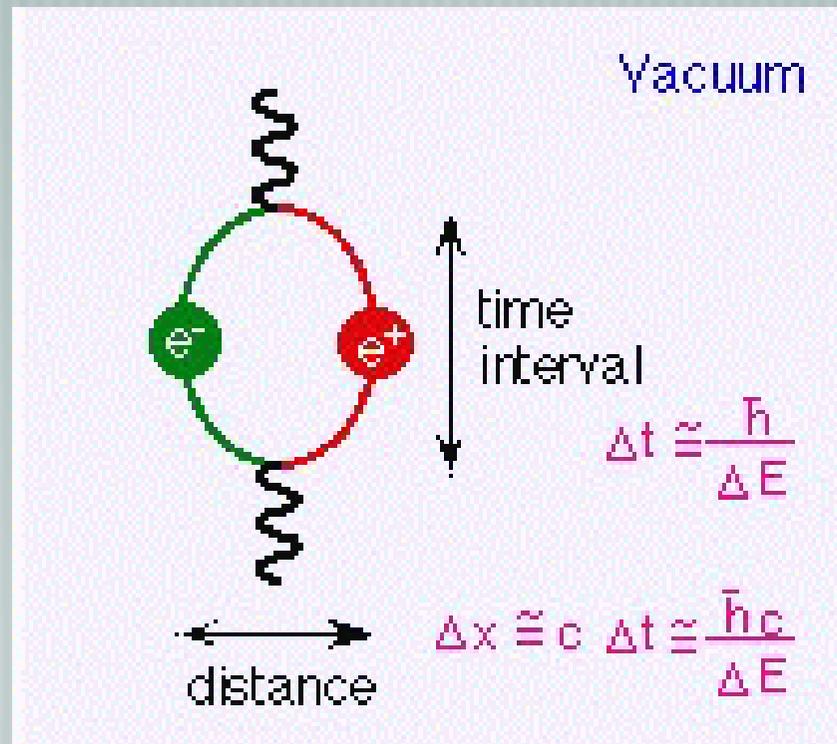
Fields

'Electromagnetic' interaction

NOW THE VACUUM HAD BECOME REALLY MESSY

Quantum physics says that 'oscillators' (e.g. field quanta) cannot be at absolute rest (uncertainty relation)

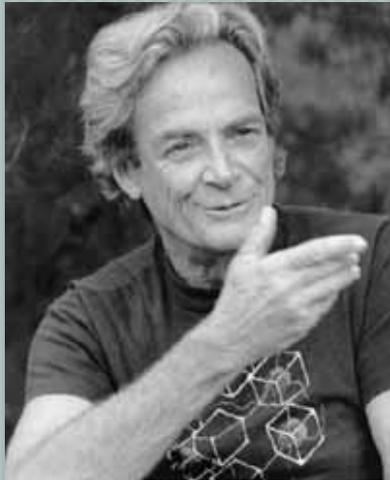
The lowest energy states of e.g. electromagnetic fields can produce (virtual) electron-positron pairs: VACUUM FLUCTUATIONS



Fields

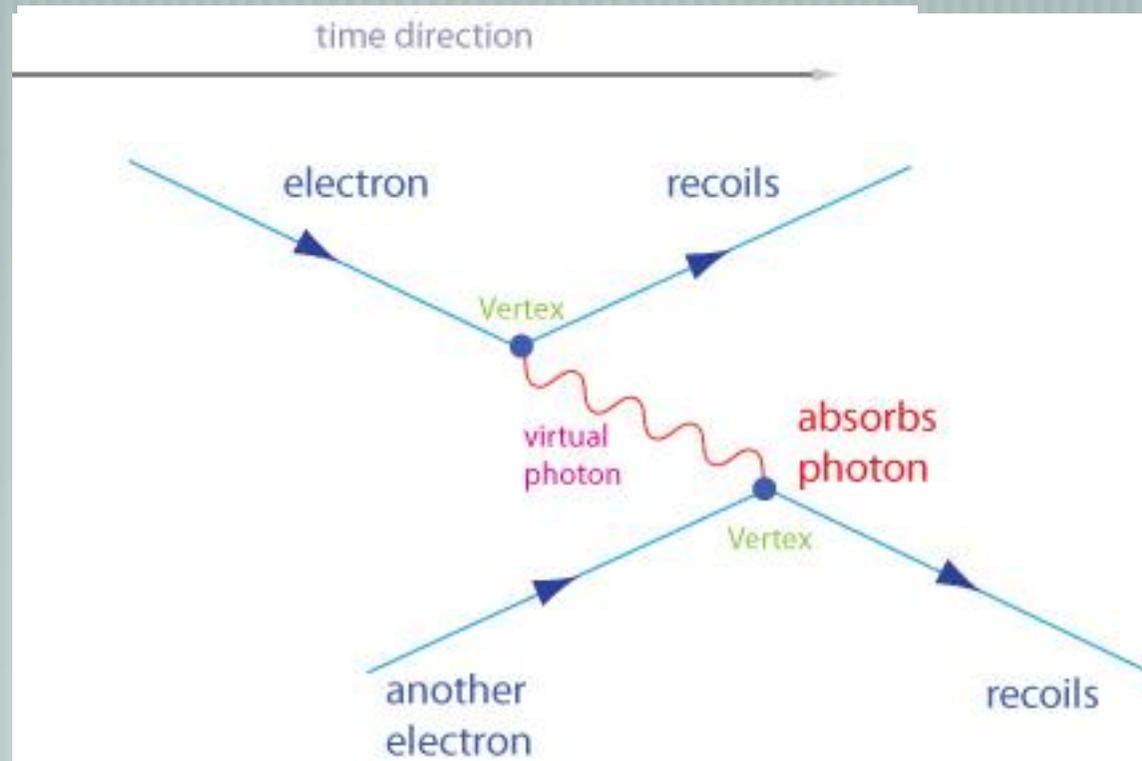
1934 - 1948

How to calculate the interaction of photons and electrons?



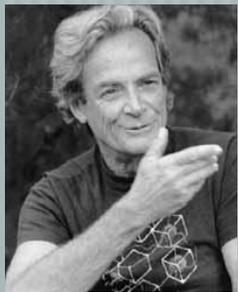
Quantum Electrodynamics

Feynman, Tomonaga, Schwinger



Fields

1934 - 1948

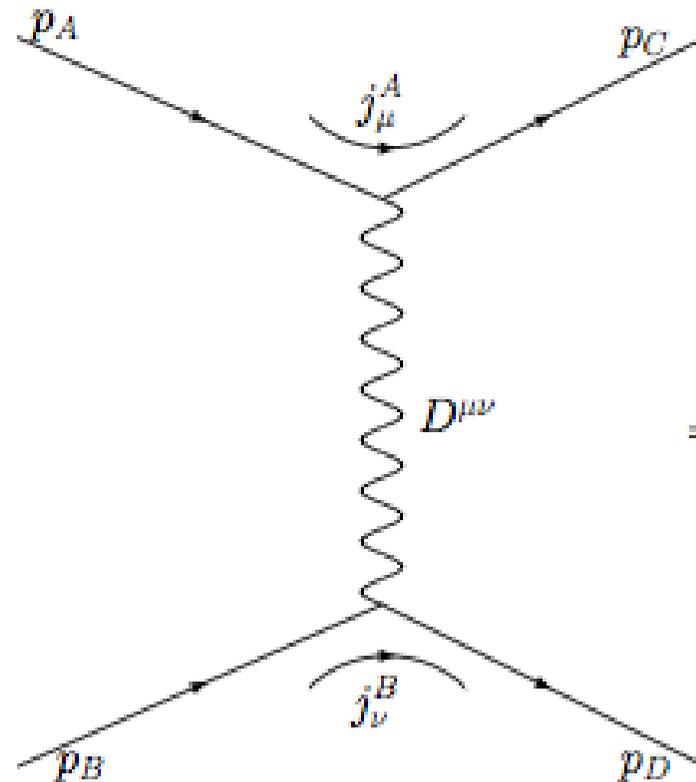


R. P. Feynman

Feynman diagrams

Precise computation rules - in graphical form

*Feynman diagrams
later became a graphical way
to represent all kinds of
particle interactions*



$$= -i \int d^4x d^4y j_\mu^A(x) D^{\mu\nu}(x, y) j_\nu^B(y)$$

Fields

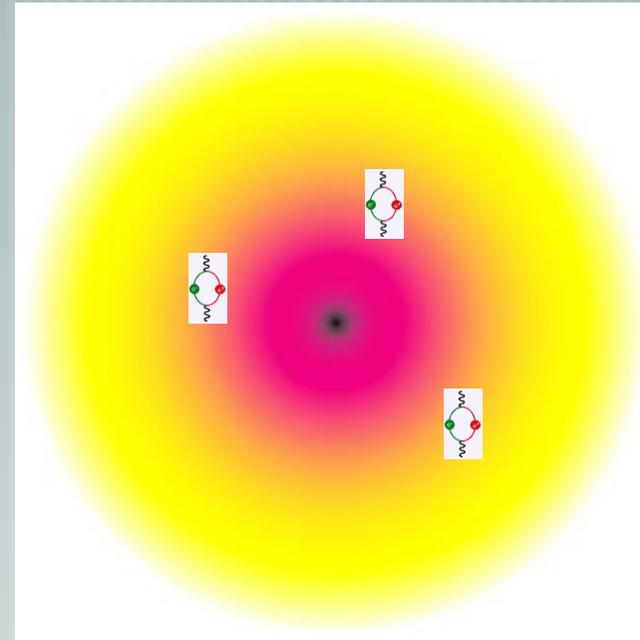
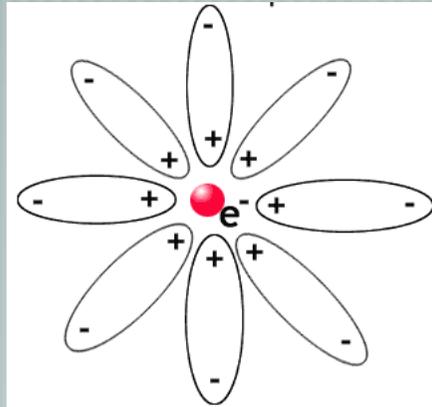
'Electromagnetic' interaction

"Renormalization"

The 'naked' electron + vacuum fluctuations = measured electron

("infinite" - "infinite" = "finite")

the **"dressed" electron**:



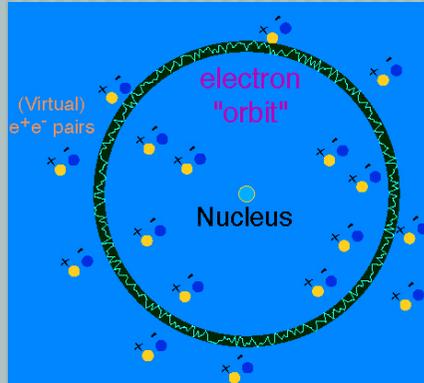
vacuum fluctuations modify its charge and mass ('Debye shielding')

Fields

1948

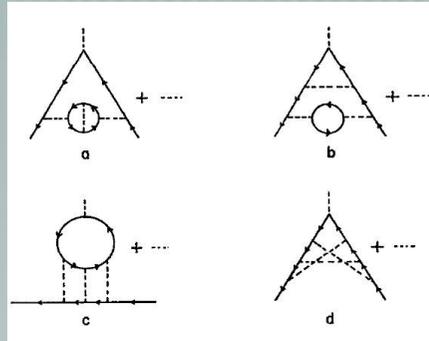
Vacuum fluctuations have observable effects

... and Quantum Electrodynamics allowed to calculate them precisely



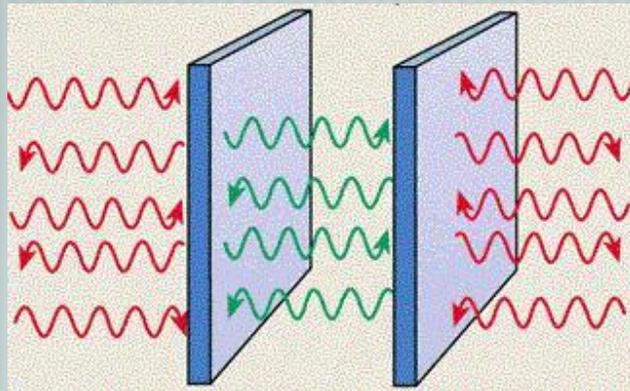
Lamb Shift

(shift of atomic energy levels)



Electron (anomalous) magnetic moment

$$\frac{1}{2}(g - 2) = \frac{1}{2} \frac{\alpha}{\pi} - 0.32848 \left(\frac{\alpha}{\pi} \right)^2 + (1.183 \pm 0.011) \left(\frac{\alpha}{\pi} \right)^3.$$



Casimir effect

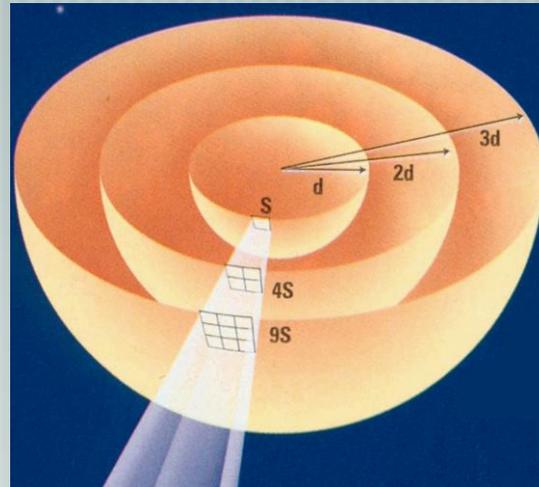
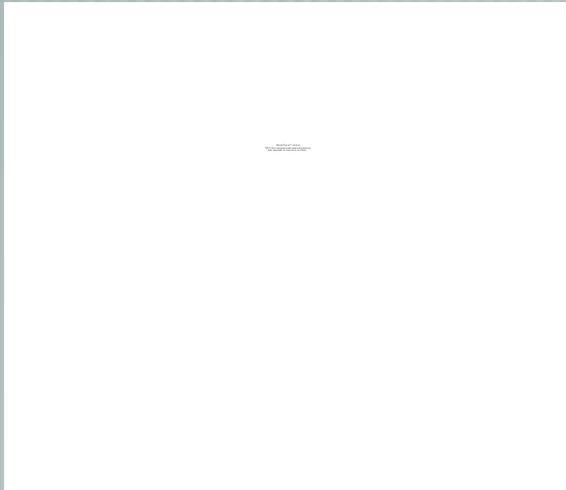
(force on two uncharged metal plates)

Fields

'Electromagnetic' interaction

QED: Charged particles interact by exchanging photons

- 1) **Massless virtual photons are continuously emitted by electric charges**
- 2) The **$1/r^2$ law** comes from the probability to hit another particle at distance r
(directly connected with the 3 dimensions of space)



$1/r^2$ law

Could that become a model for other interactions?