PARTICLE PHYSICS AND COSMOLOGY

in the 20th century

Rolf Landua
CERN

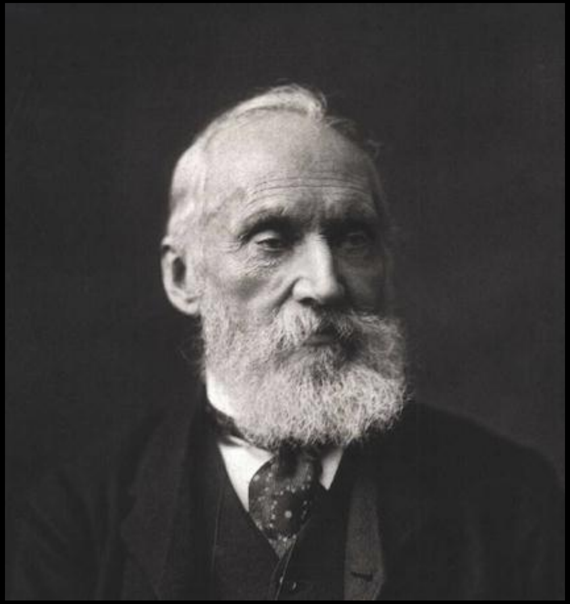
DISCLAIMER

100 year of ideas, theories and experiments on particle physics and cosmology.

50+ Nobel prizes

Broad overview - not comprehensive, not in-depth

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)

Except 'two clouds' on the horizon of physics:

1) Blackbody radiation
2) Michelson-Morley experiment

...and: are "atoms" real ???

1900

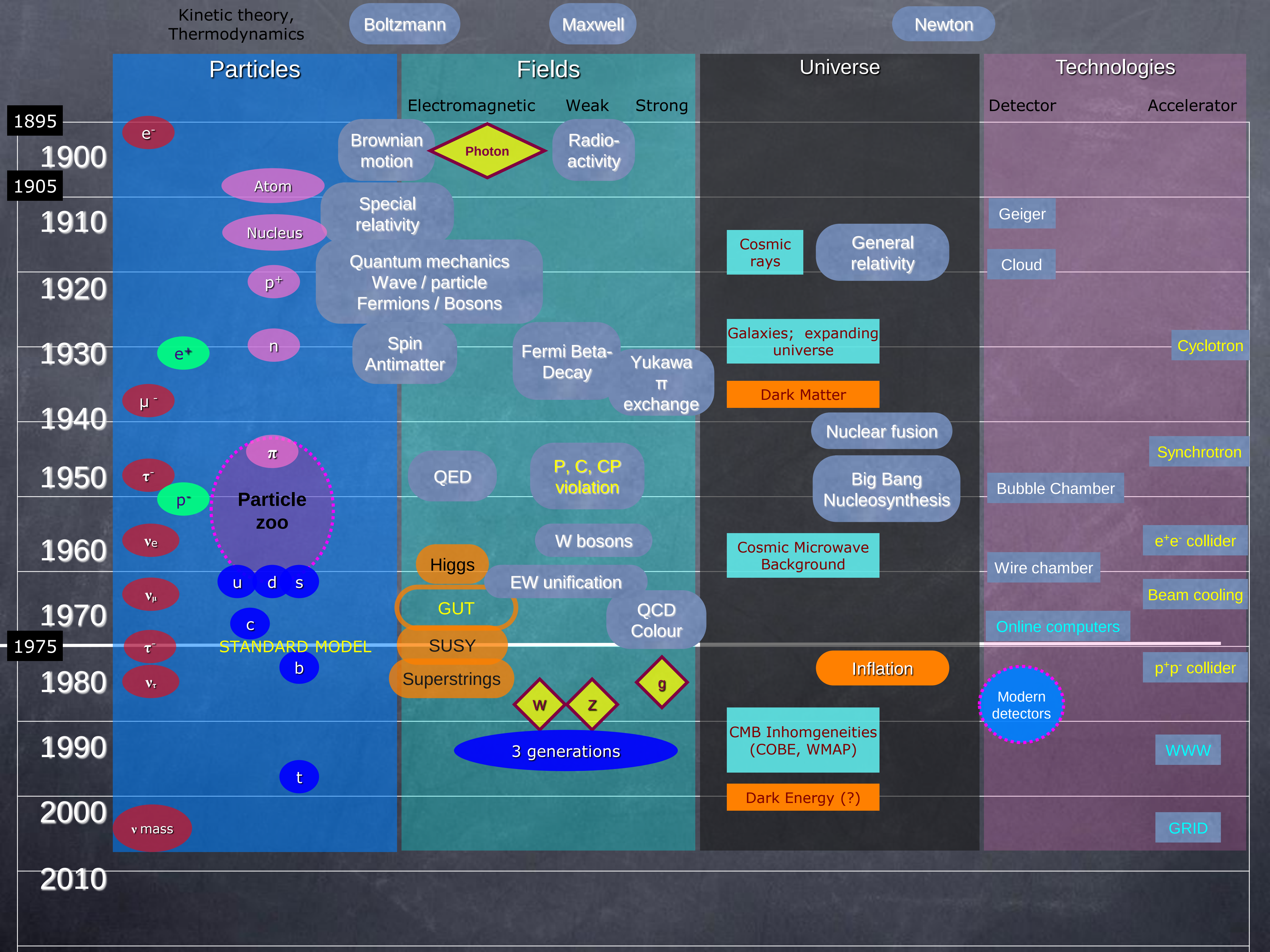
Universe = solar system and the stars of our galaxy

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



Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Universe
Technologies
Electromagnetic
Weak
Strong
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e^-
Atom
Nucleus
p^+
e^+
n
μ^-
π
τ^-
p^-
Particle zoo
ν_e
u
d
s
ν_μ
c
STANDARD MODEL
τ^-
b
ν_τ
t
ν mass
Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Spin
Antimatter
Fermi Beta-Decay
Yukawa
π
exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD
Colour
SUSY
Superstrings
W
Z
g
3 generations
Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
Nuclear fusion
Big Bang Nucleosynthesis
Cosmic Microwave Background
Inflation
CMB Inhomgeneities (COBE, WMAP)
Dark Energy (?)
Geiger
Cloud
Cyclotron
Synchrotron
Bubble Chamber
e^+e^- collider
Wire chamber
Beam cooling
Online computers
p^+p^- collider
Modern detectors
WWW
GRID

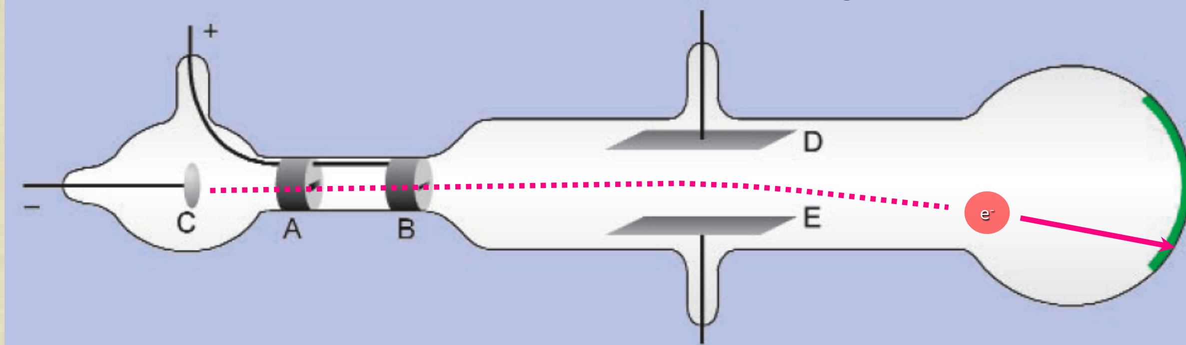
1 PARTICLE SPECTRUM

1897

e^-

J.J. Thomson

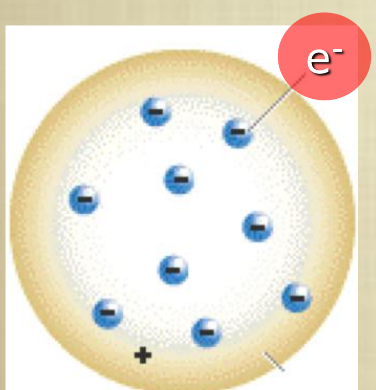
Electrodes D+E : electric field
External coils: magnetic field



Cathode ray experiments (~ TV)

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

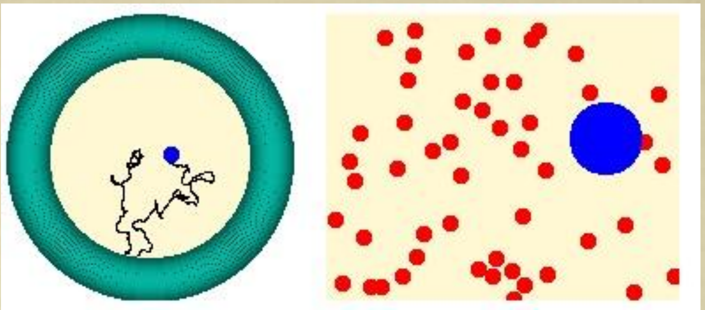
***later called 'electrons'**



His 'plumpudding' model
of the atom (1904)

Electrons are sub-atomic particles!

PARTICLE SPECTRUM



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

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

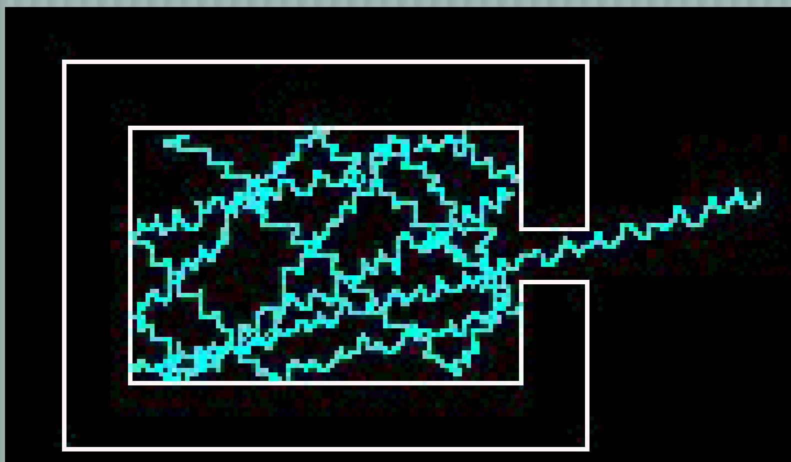
The existence of atoms was proven

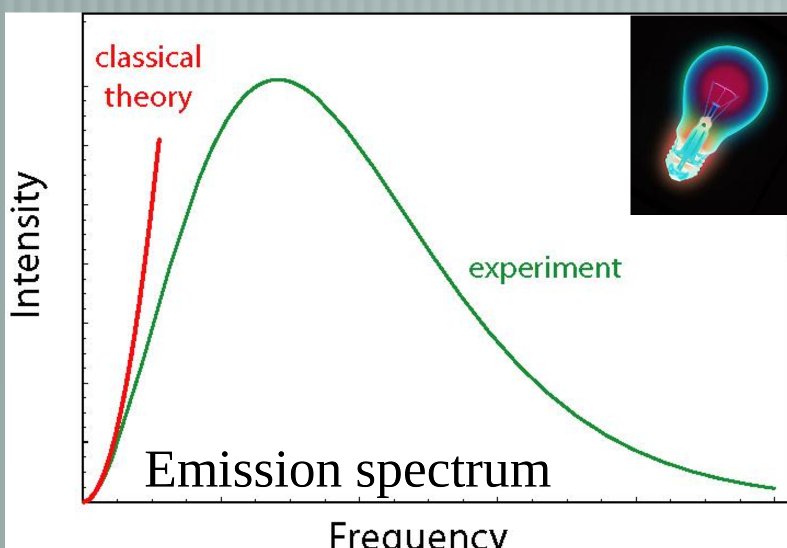
Fields

Photon

'Electromagnetic' interaction

Blackbody radiation





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

"Radiation function" = f(T) only

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

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 ’ **$\varepsilon = h\nu$**

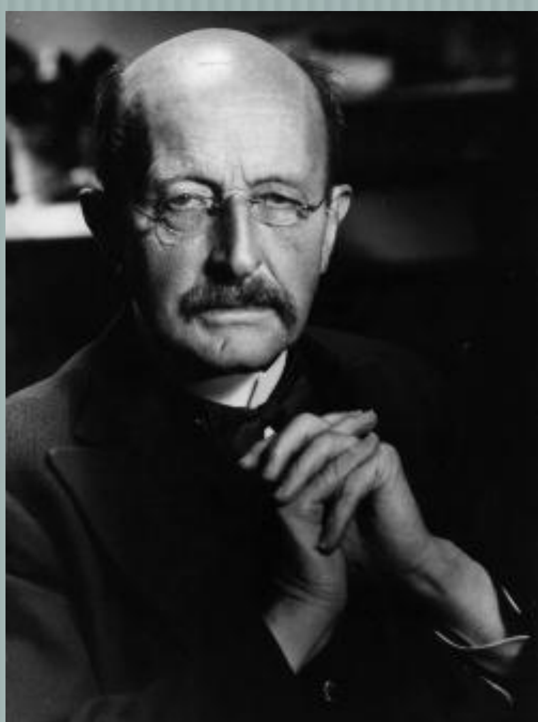
Higher frequency means bigger chunks, so it is less likely to find $E >> kT$

average energy of oscillators

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

h = new fundamental constant

14 December 1900



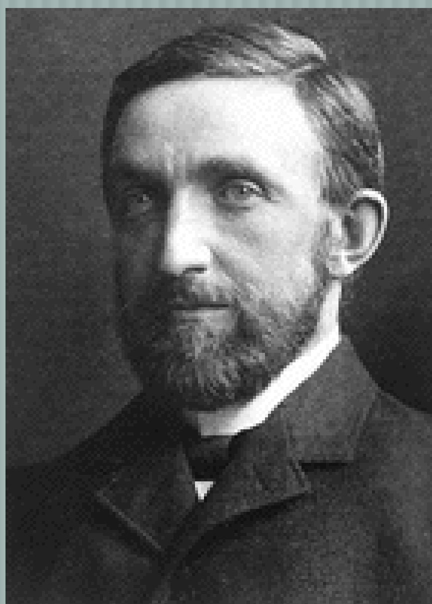
Max Planck

Fields

'**Electromagnetic' interaction**

Photon

1902

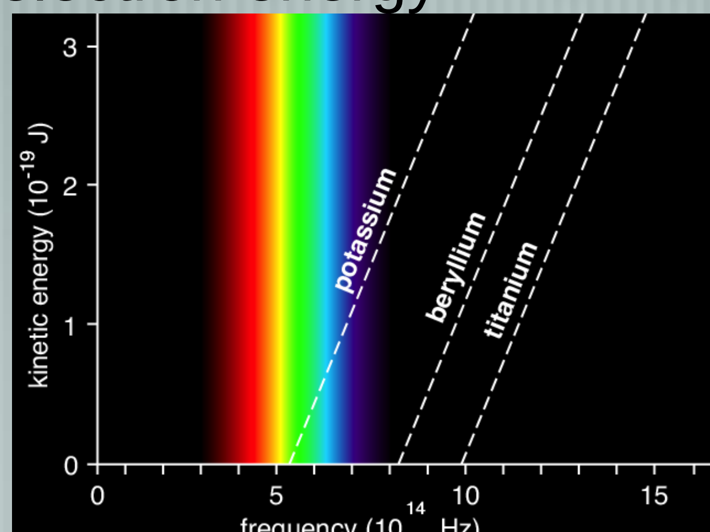


Philipp von Lenard

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



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

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

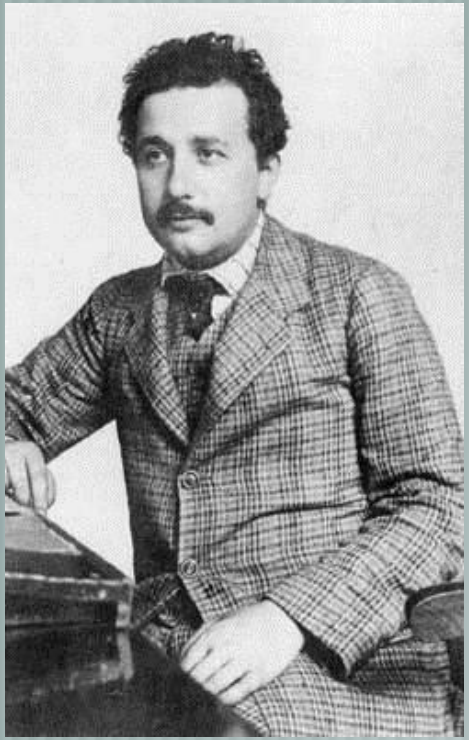
Fields

Photon

'Electromagnetic' interaction

"My only revolutionary contribution"

17 March 1905



Albert Einstein

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

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

"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")

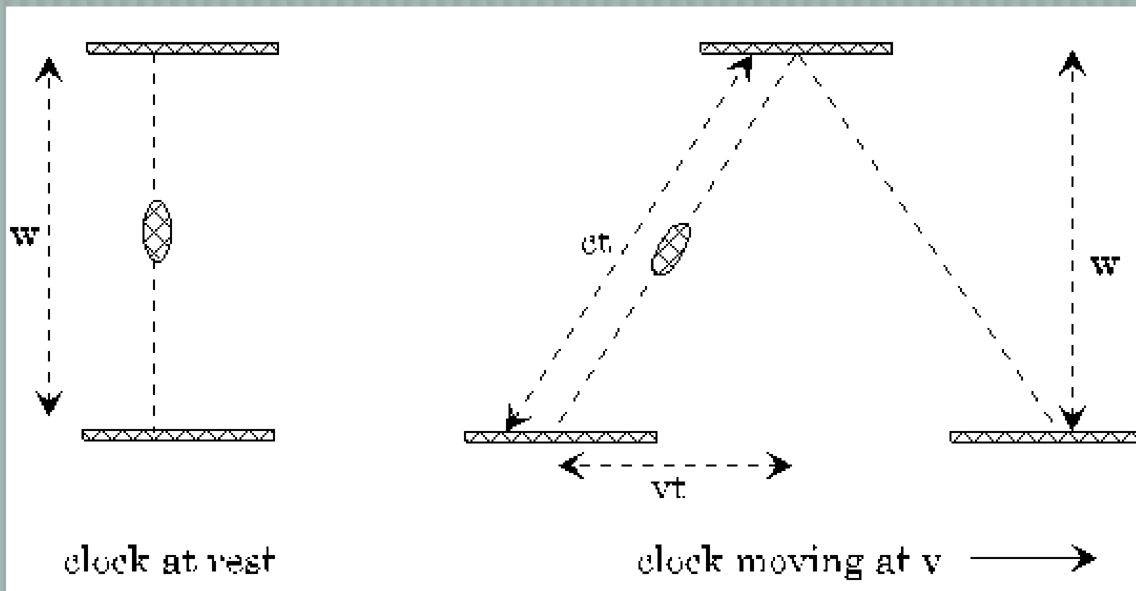
His conclusions:

Since c = constant and speed = (space interval/time interval) -->

space and time cannot be absolute!

Fields

Special relativity



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

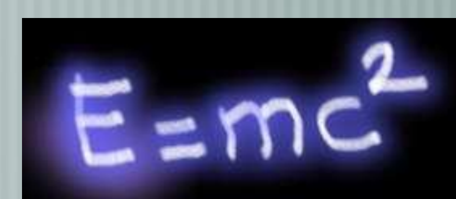
$t^2(c^2 - v^2) = w^2$

$$t = \frac{w/c}{\sqrt{1 - \frac{v^2}{c^2}}} = g \times t$$

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

1) Time dilation, space contraction

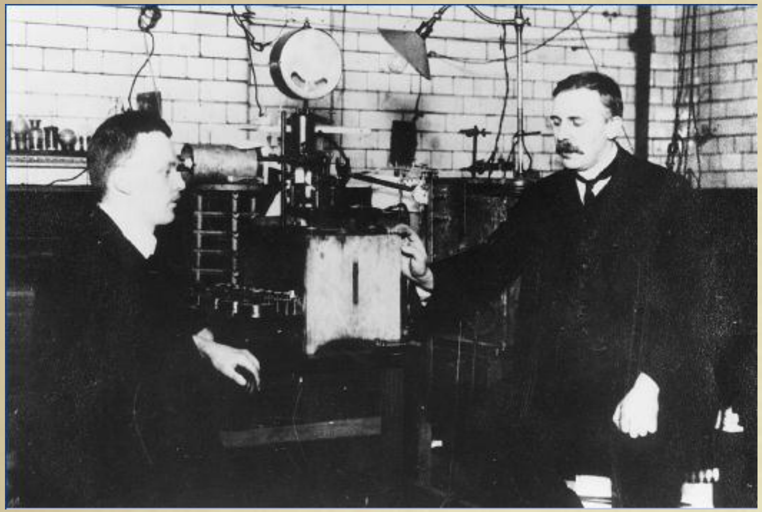
2) Modification of Newton's laws, relativistic mass increase.



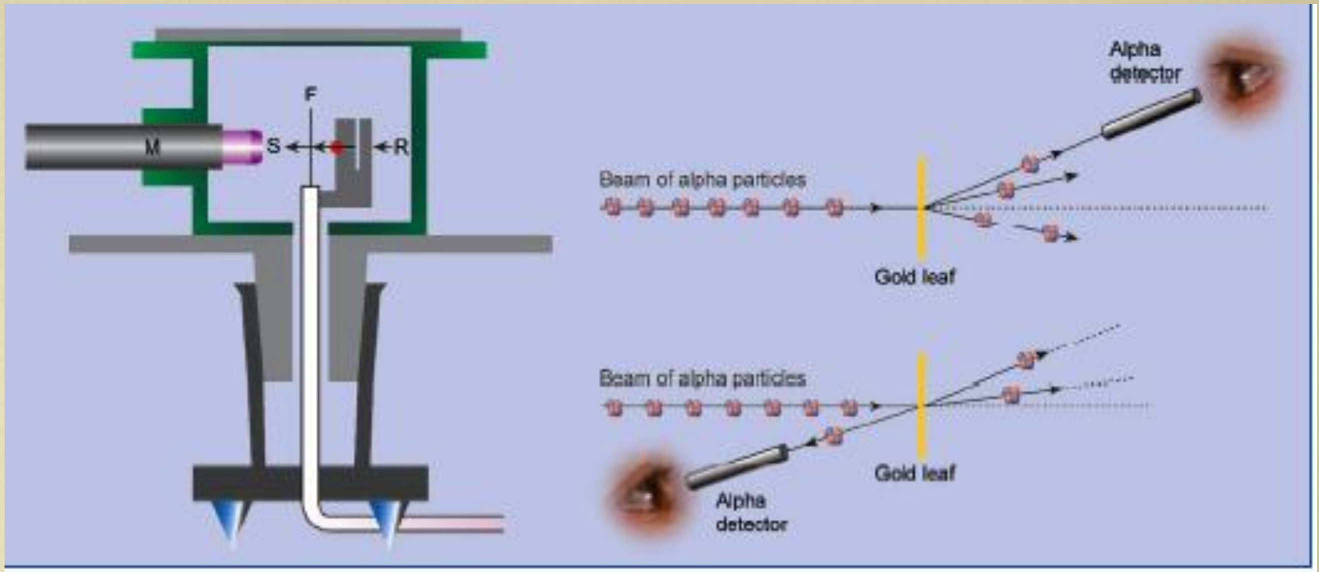
PARTICLE SPECTRUM

Nucleus

1911



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 deg)

This could not be explained by the 'plumpudding model'

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

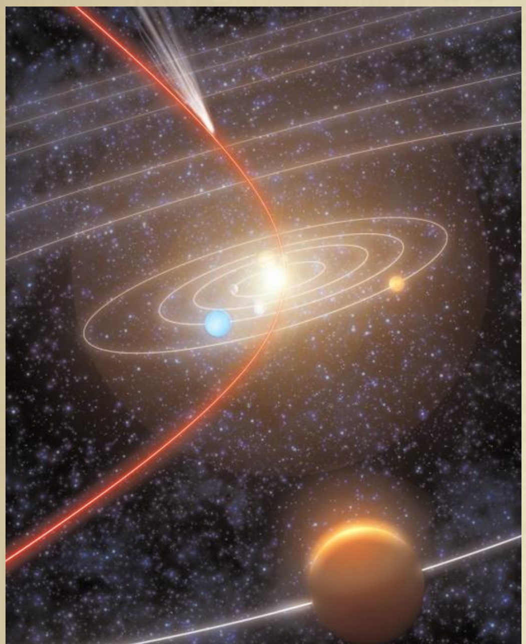
Size: At minimum distance, Coulomb repulsion = kinetic energy: ~ 27×10^{-15} m (true value: 7.3)

Discovery of the nucleus

Nucleus

PARTICLE SPECTRUM

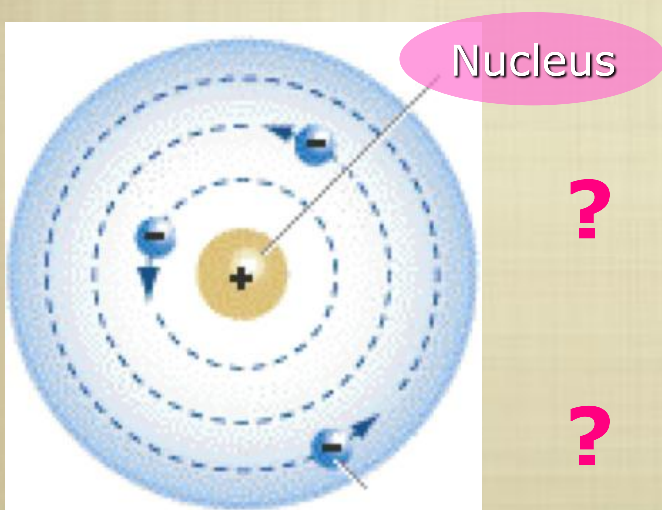
1911



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



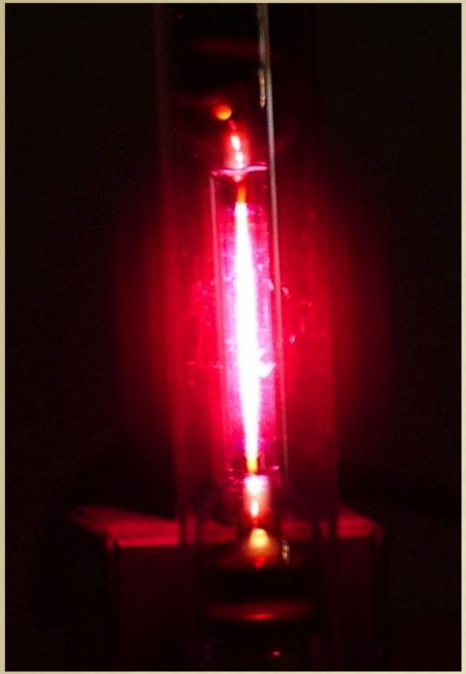
Rutherford's model
of the “empty” atom

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

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

PARTICLE SPECTRUM

1913



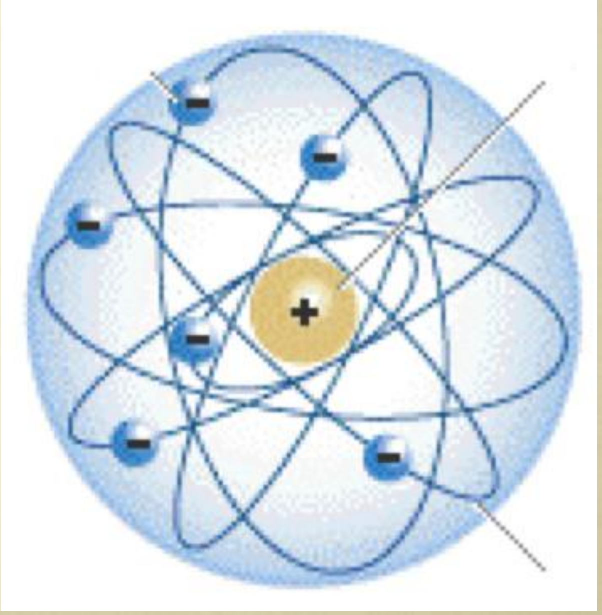
J. J. Balmer (1885) observed the emission spectrum of hydrogen

His empirical formula:

$$\lambda = \frac{hm^2}{(m^2 - n^2)}$$

Niels Bohr visited Rutherford in 1913

he was the first to apply quantum ideas to atoms



- Quantization of angular momentum -> energy levels

$$\mathbf{L} = n \cdot \hbar = n \cdot \frac{h}{2\pi} \qquad E_n = \frac{-13.6\ \mathrm{eV}}{n^2}$$

- Emission of radiation only during transitions
- Energy of photons = difference of energy levels

PARTICLE SPECTRUM

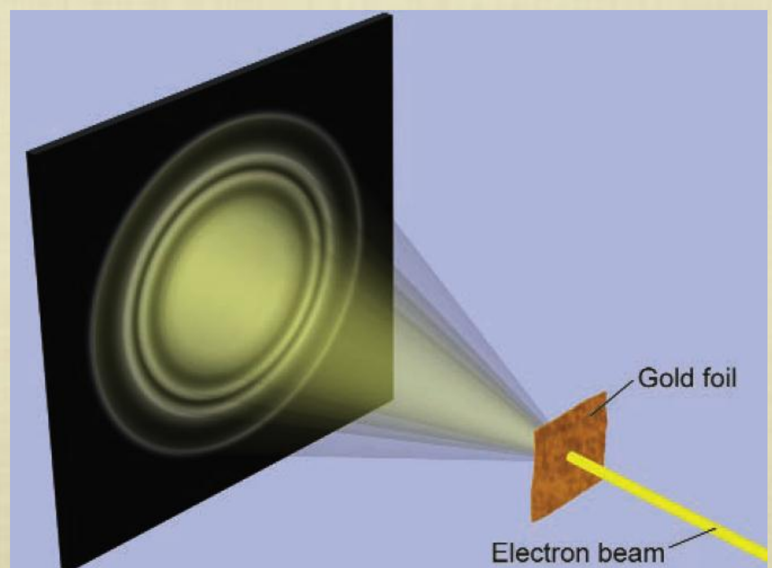
1923-1927

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)

PARTICLE SPECTRUM

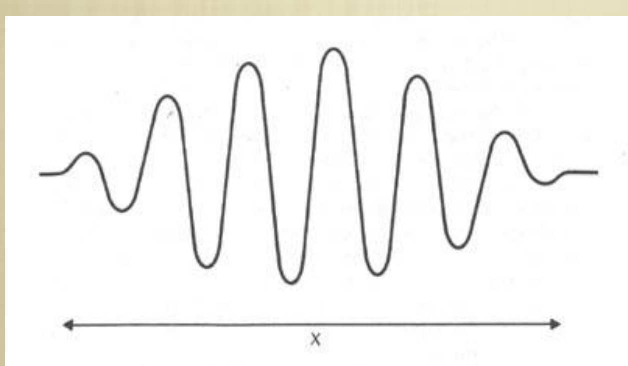
1923-1927

Heisenberg (1925)

Uncertainty relation

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

Position and momentum $$\Delta x \Delta p \geq \frac{\hbar}{2}$$



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

Analogy:

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

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

Energy and time $$\Delta E \Delta t \geq \hbar$$

PARTICLE SPECTRUM

1923-1927

Schrödinger
1926

Probability wave function

If particles are waves -> describe by a wave equation

Interference: ψ should be complex function

How did Schrödinger guess his equation ?

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”:

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

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

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:

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

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

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

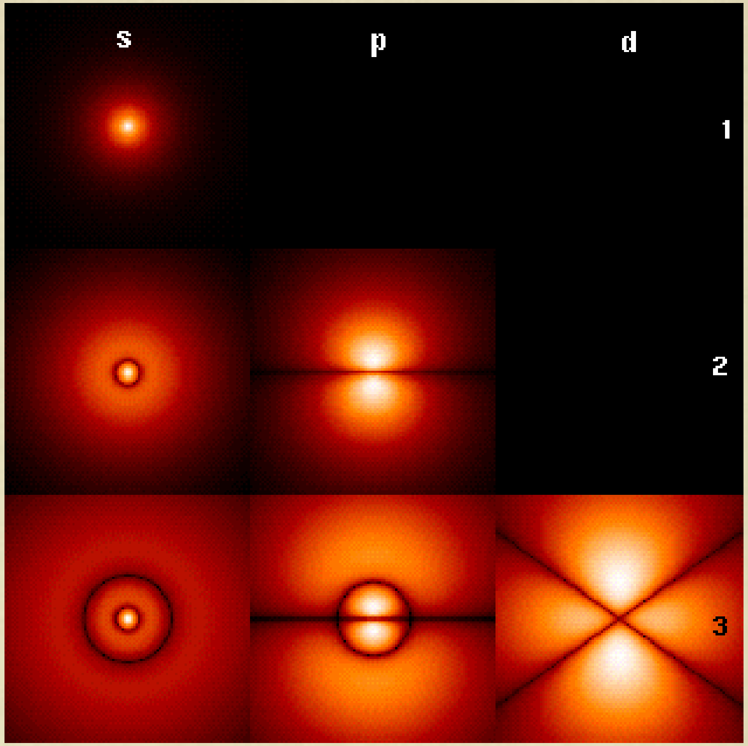
Schrödinger equation:

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

PARTICLE SPECTRUM

1923-1927

Hydrogen 'standing wave' functions



Interpretation (Born, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability

Excellent description
if v << c

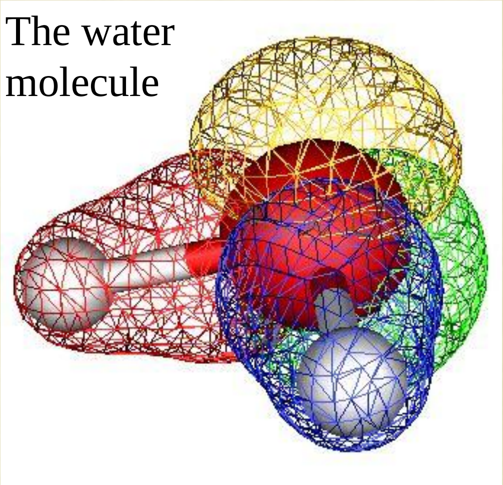
PARTICLE SPECTRUM

1928

Quantum physics explained the existence of 'structure' in nature

The nature of chemical bonds

Linus Pauling (1928)



Atoms, Molecules and the origin of structure were understood.

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

Fields

Quantum theory + special relativity = Dirac equation

Laws of Nature must treat space and time coordinates equally

The 'linearized' energy-momentum relation

$$\boxed{\begin{aligned} &E^2 = p^2 + m^2 \rightarrow \\ &E = \pm(\alpha \cdot p) + \beta m \end{aligned}}$$

Paul A.M. Dirac
(1928)

Compare: non-relativistic Schrödinger equation

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

Fields

Quantum theory + special relativity = Dirac equation

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

$$\Psi = \begin{pmatrix} \text{Elektron - Spin up} \\ \text{Elektron - Spin down} \\ \text{Positron - Spin up} \\ \text{Positron - Spin down} \end{pmatrix}$$

1) ANTI-PARTICLES (NEW !)
2) SPIN 1/2 (explained)
3) SPIN 1/2 particles obey exclusion principle (1940)

Fields

‘Electromagnetic’ interaction

Two crucial (theoretical) predictions by Dirac

The wave function has 4 components (two spin 1/2 particles)

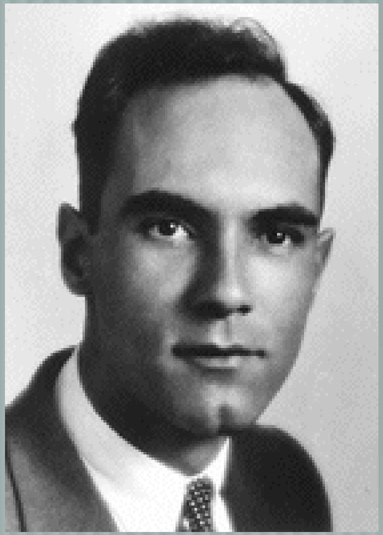
2 components for particle - and 2 components for antiparticle!

Every particle has an antiparticle !

Fields

e^+

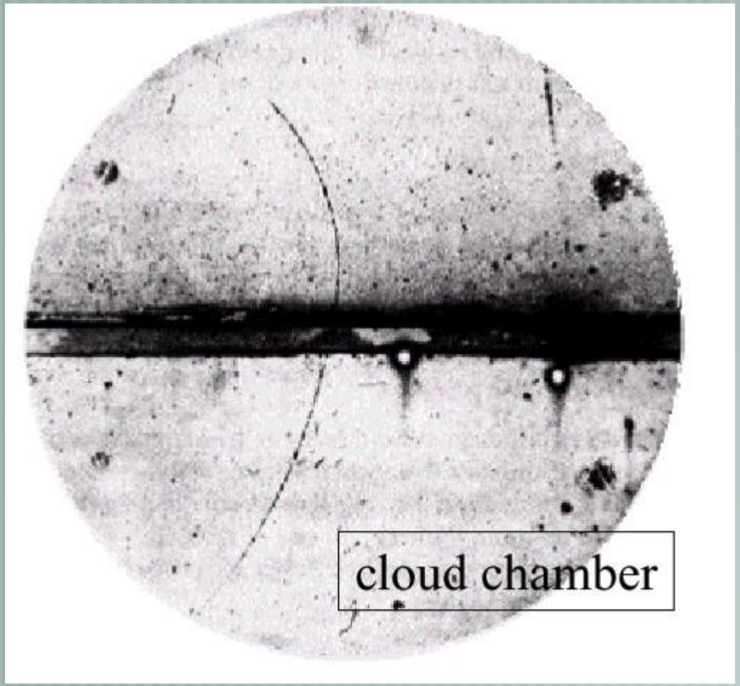
'Electromagnetic' interaction

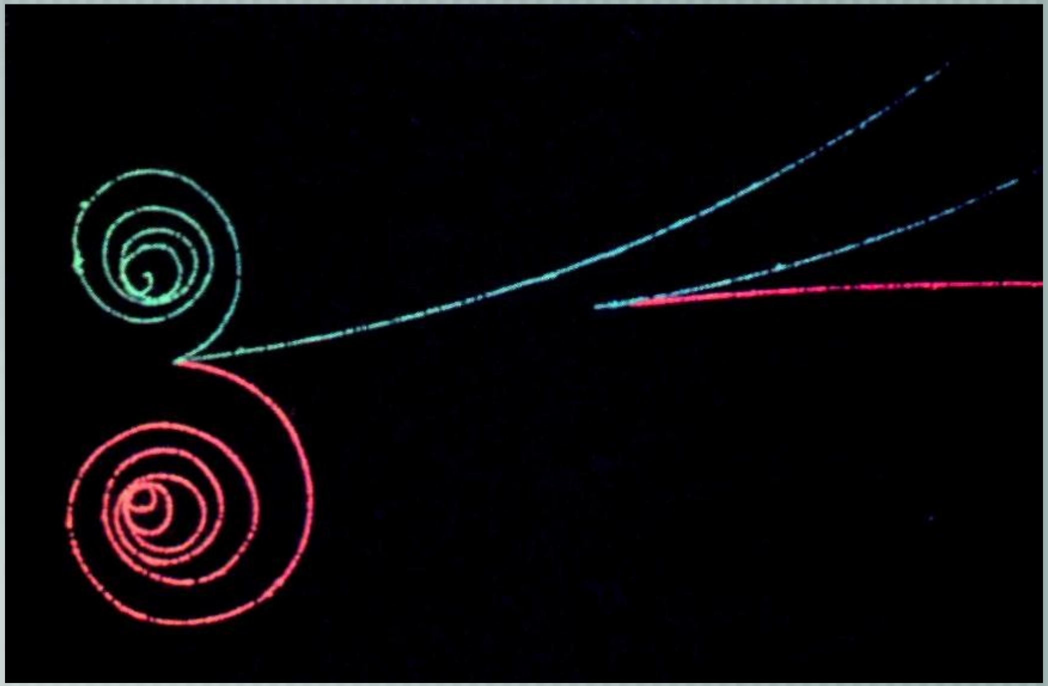


Discovery of the positron

Dirac was right!

Anderson (1932)





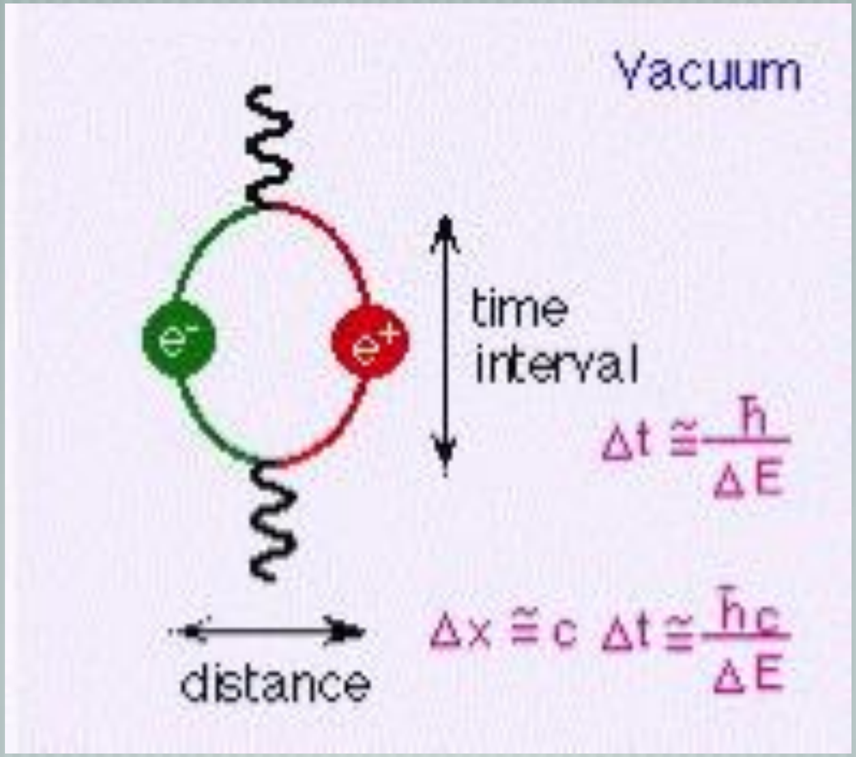
Fields

'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

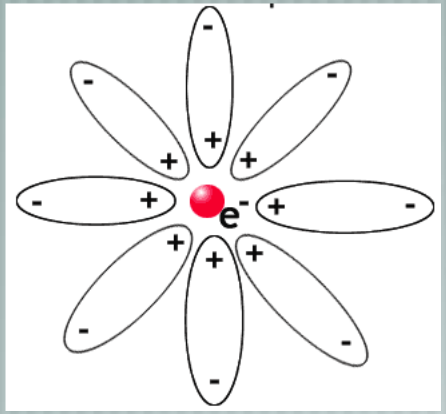
'Electromagnetic' interaction

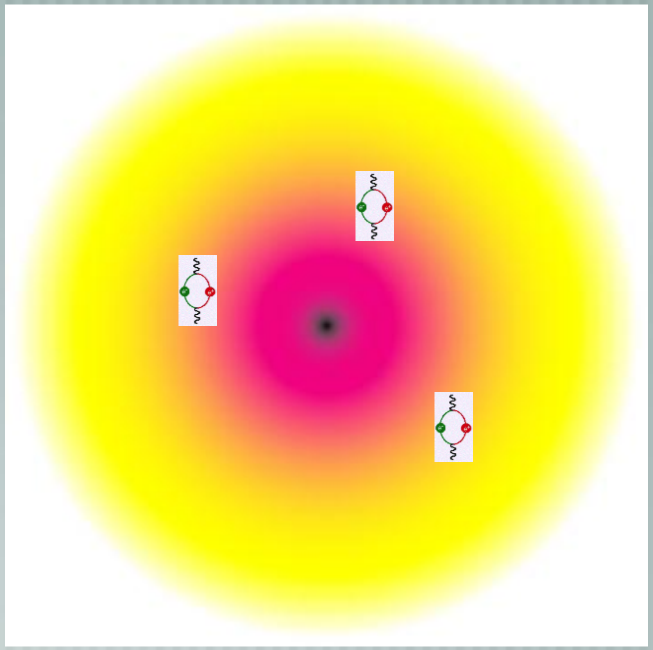
"Renormalization"

The 'naked' electron + vacuum fluctuations = measured electron

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

the **"dressed" electron**:





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

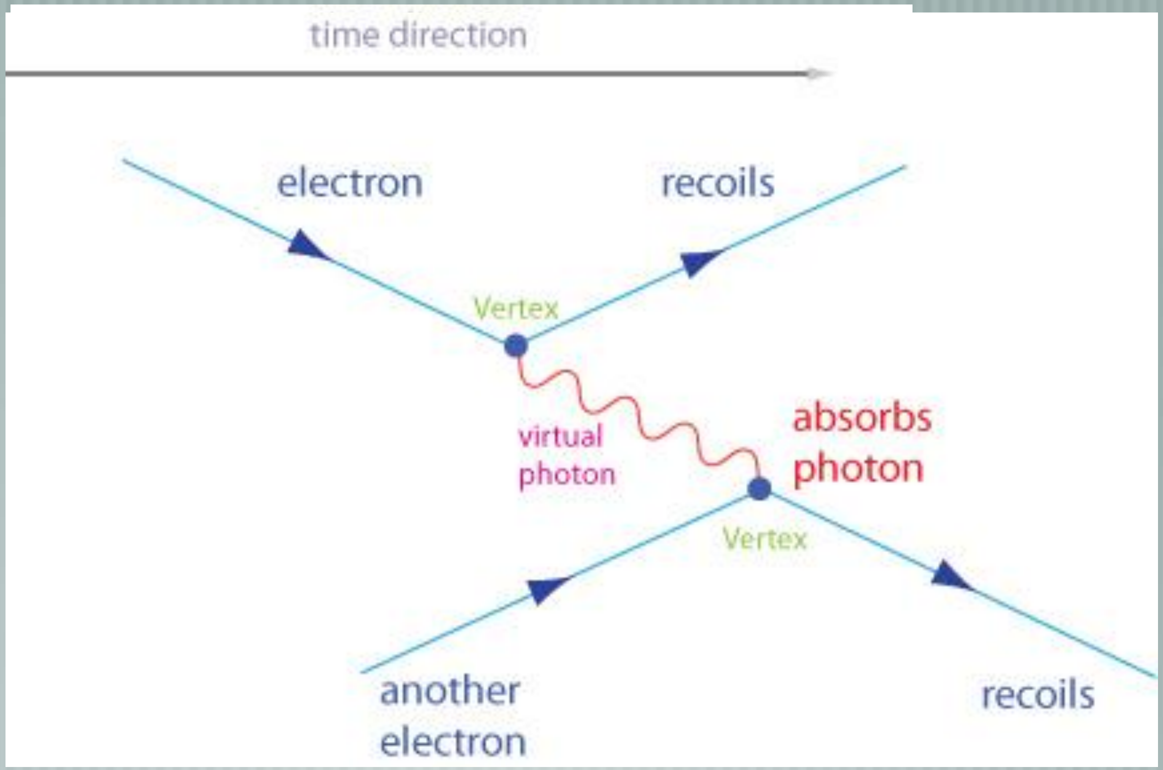
Fields

1934 - 1948

How to calculate the interaction of photons and electrons?

Quantum Electrodynamics

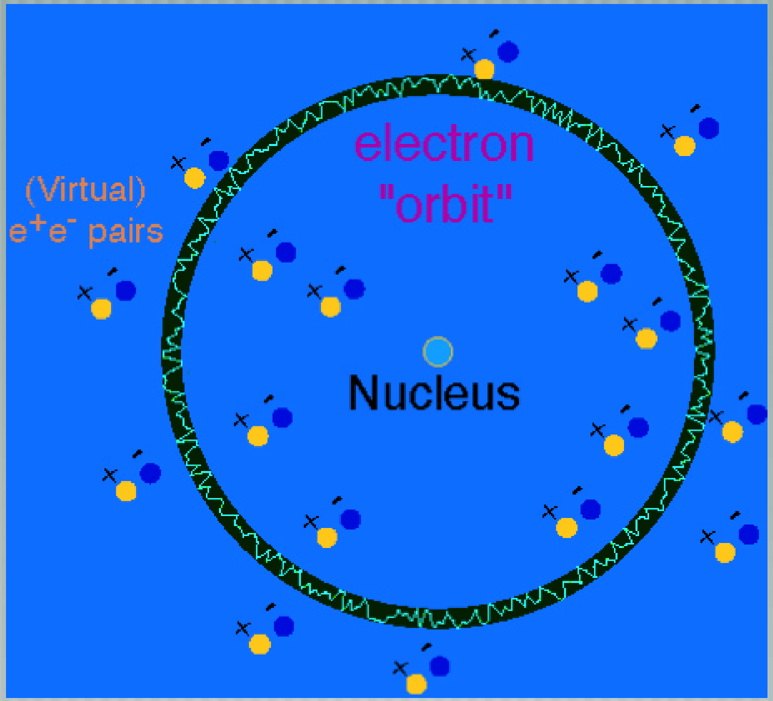
Feynman, Tomonaga, Schwinger



Fields

1948

QED first success: correct prediction of energy shifts in hydrogen



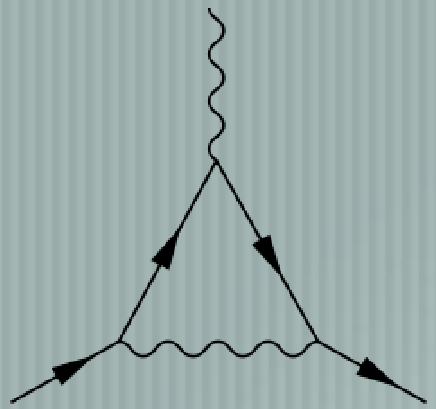
Lamb Shift

(Shift of energy level by about 10^{-6} of 1S-2S energy difference)

Felder

1948

Huge success of QED: Prediction of small effects by vacuum fluctuations



The "anomaly" of the magnetic moment of the electron

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

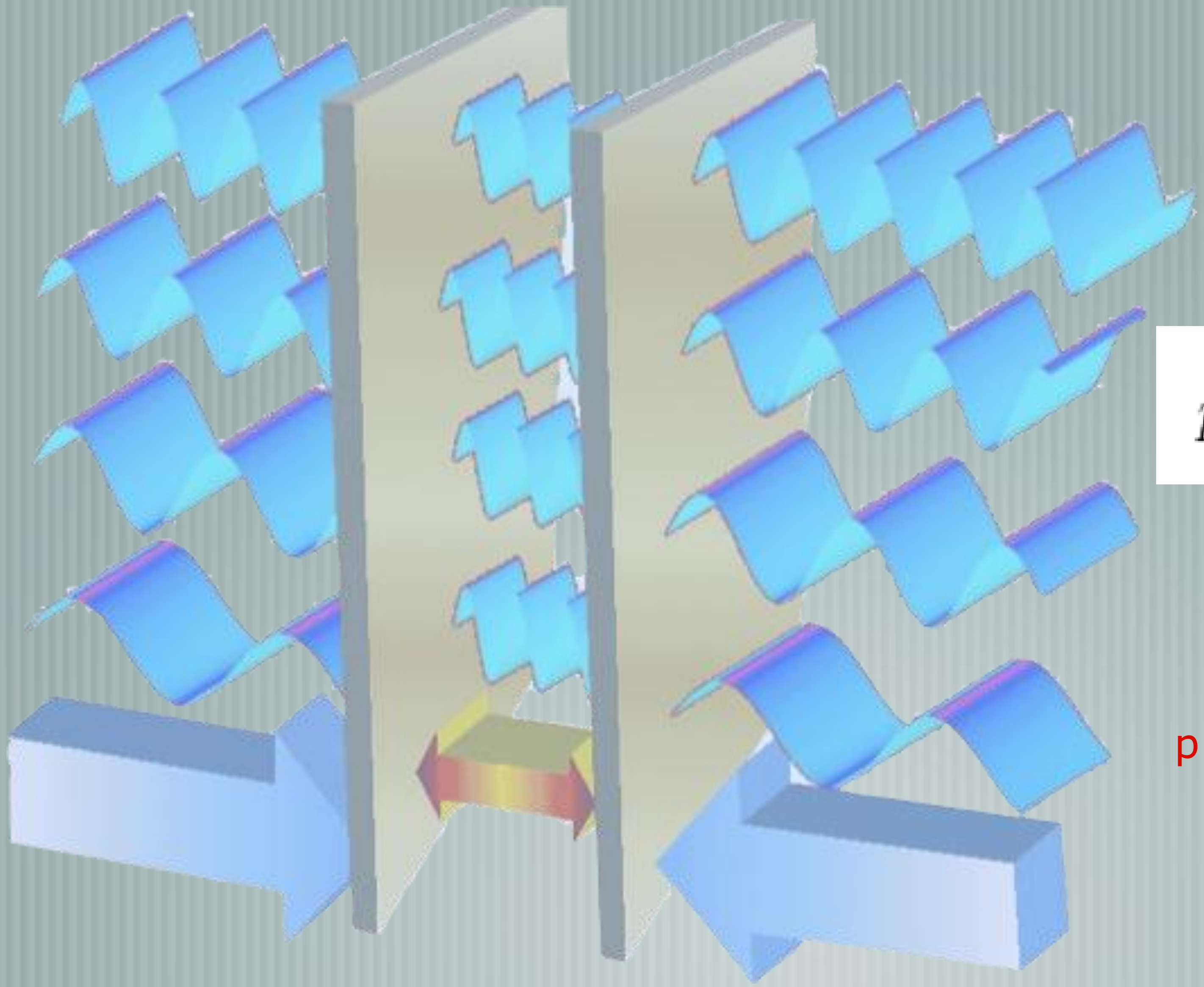
Measured: $a = 0.00115965218073(28)$

agrees to 10 significant digits with theoretical prediction !!

Casimir effect

1948

Force between two uncharged metal plates



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

p = 100 kPa (d=11 nm)

Fields

The origin of the $1/r^2$ law

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

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

Gravitation

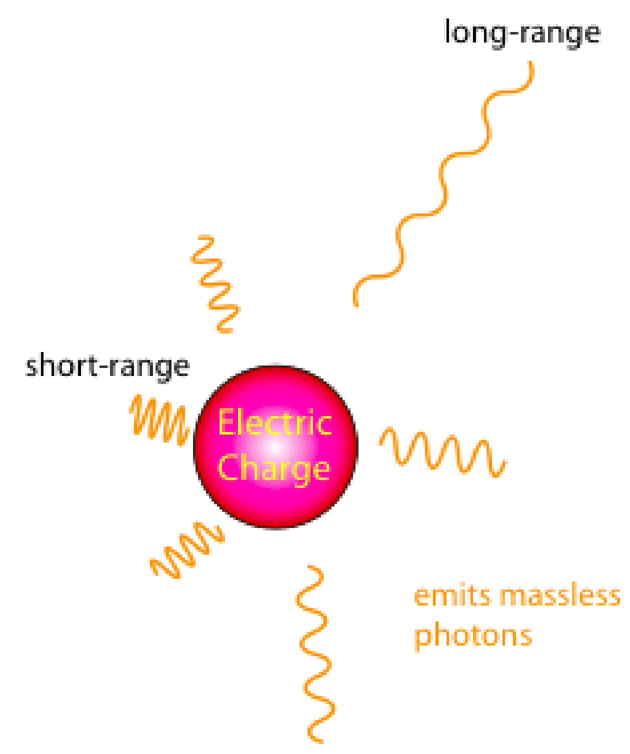
Electromagnetism

Similarities: both have inverse square dependence on radius

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

Fields

The origin of the $1/r^2$ law



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

Coulomb law

Fields

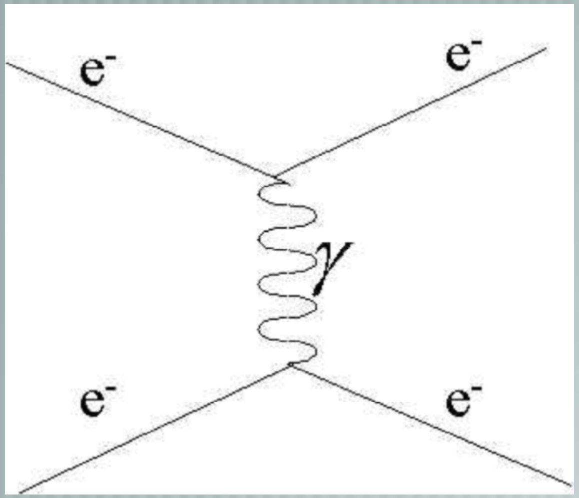
'Electromagnetic' interaction

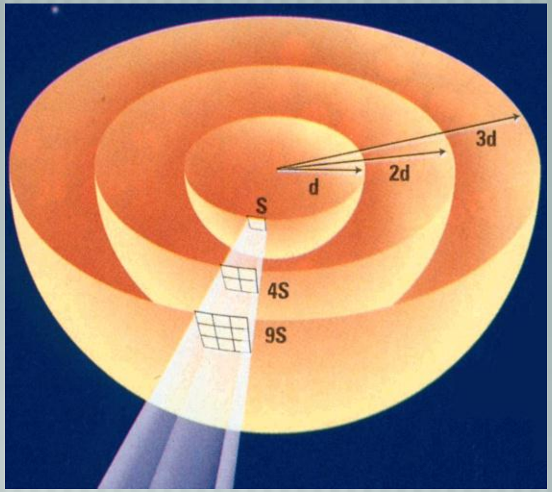
QED: Charged particles interact by exchanging photons

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?