HISTORY OF PARTICLE PHYSICS

in the 20th century

Rolf Landua
CERN

Lecture 1 - From the electron to the particle zoo

DISCLAIMER

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

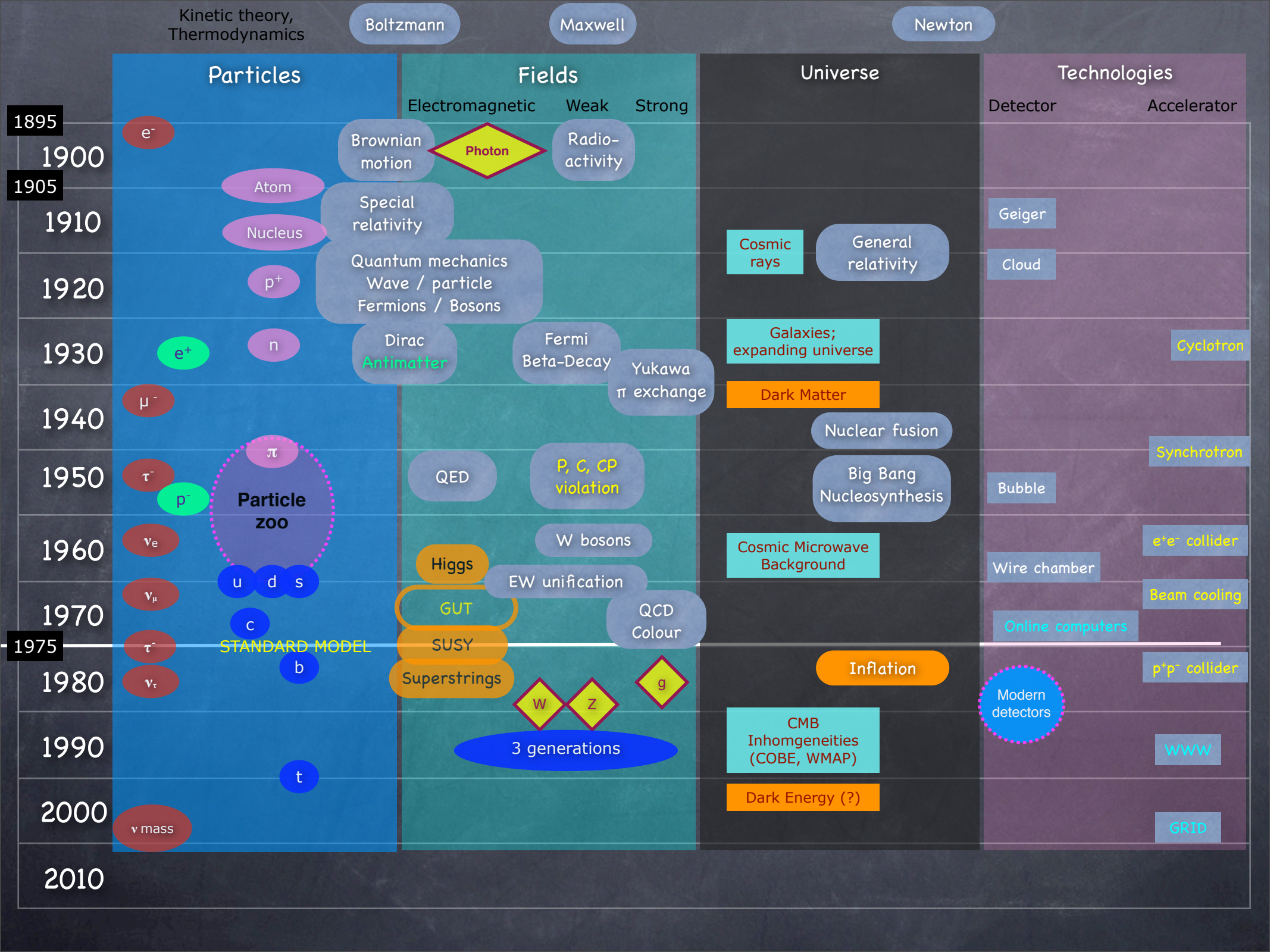
More than 50 Nobel prize winners on particle physics

Very difficult to be comprehensive, exact or in-depth

Overview ('road map') about HST programme

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

(Albert Michelson, 1894)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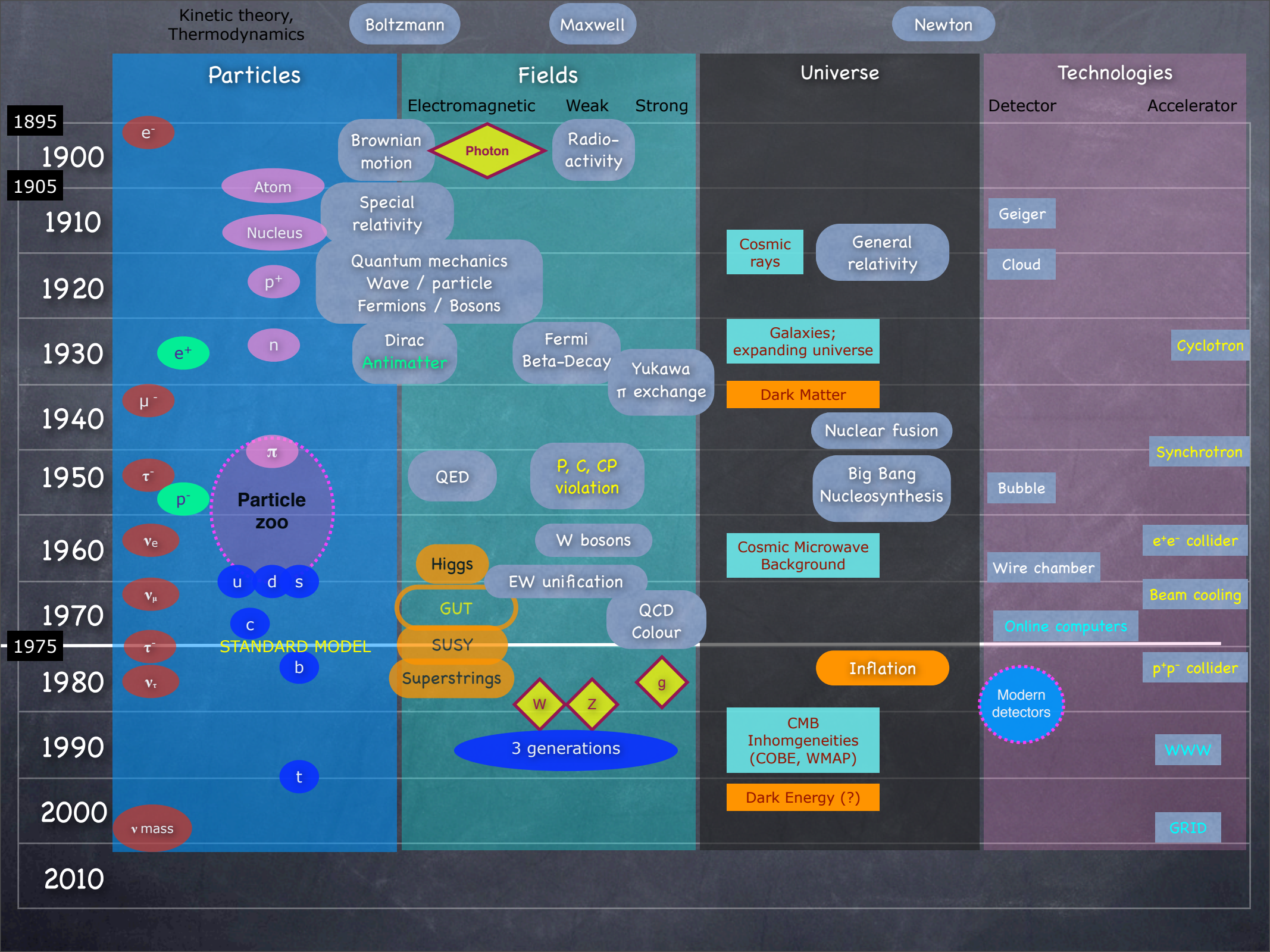
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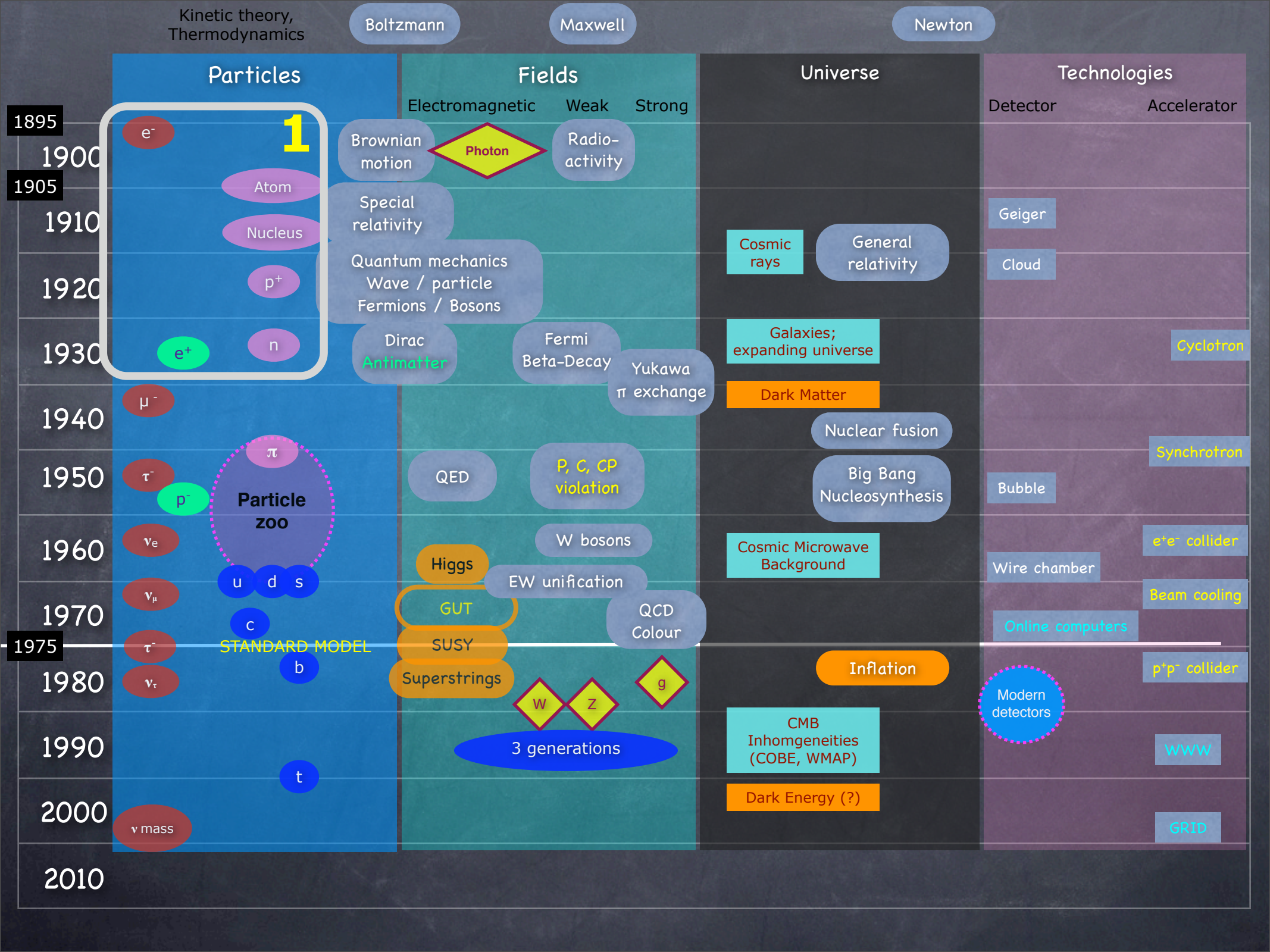
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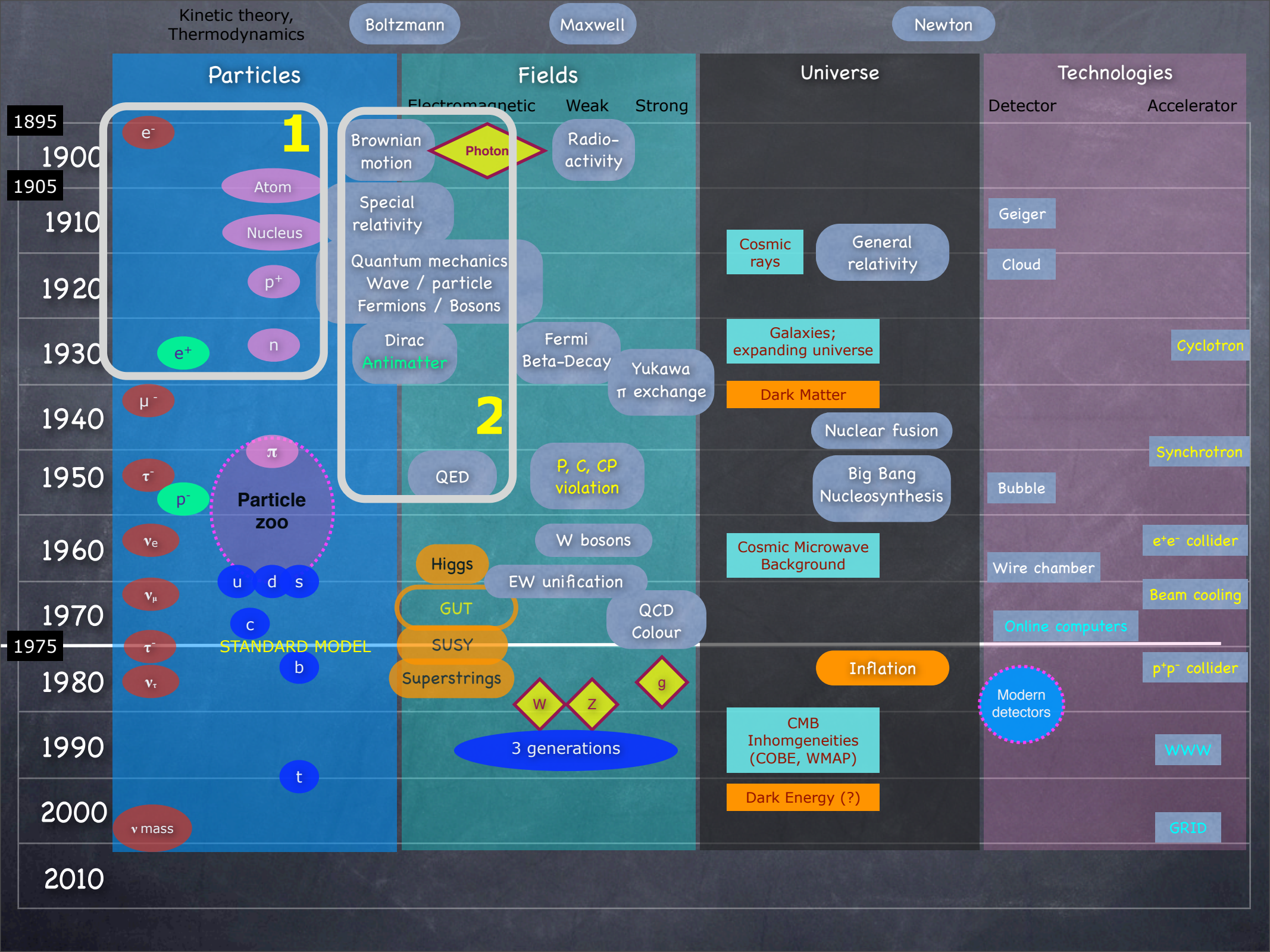
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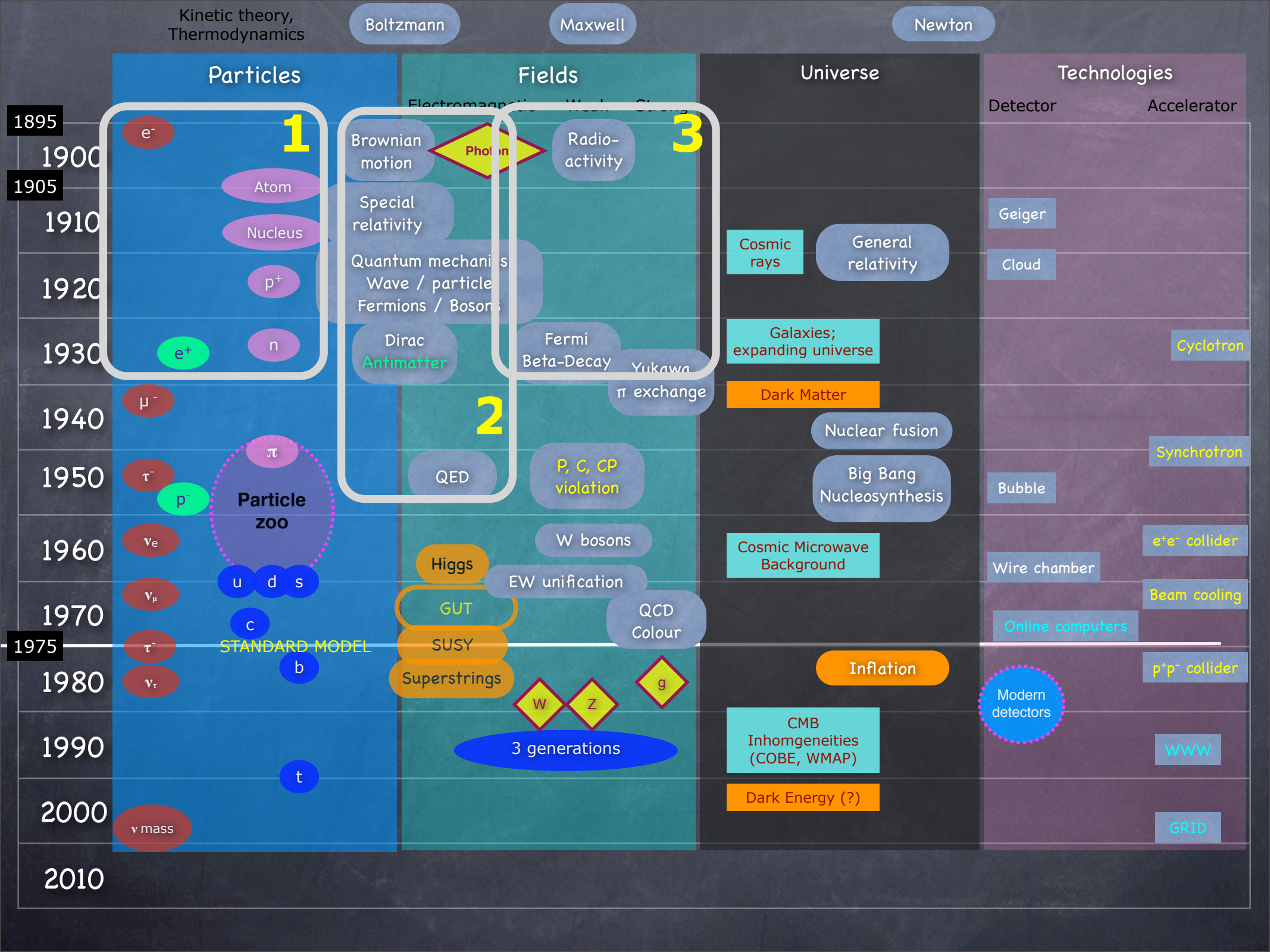
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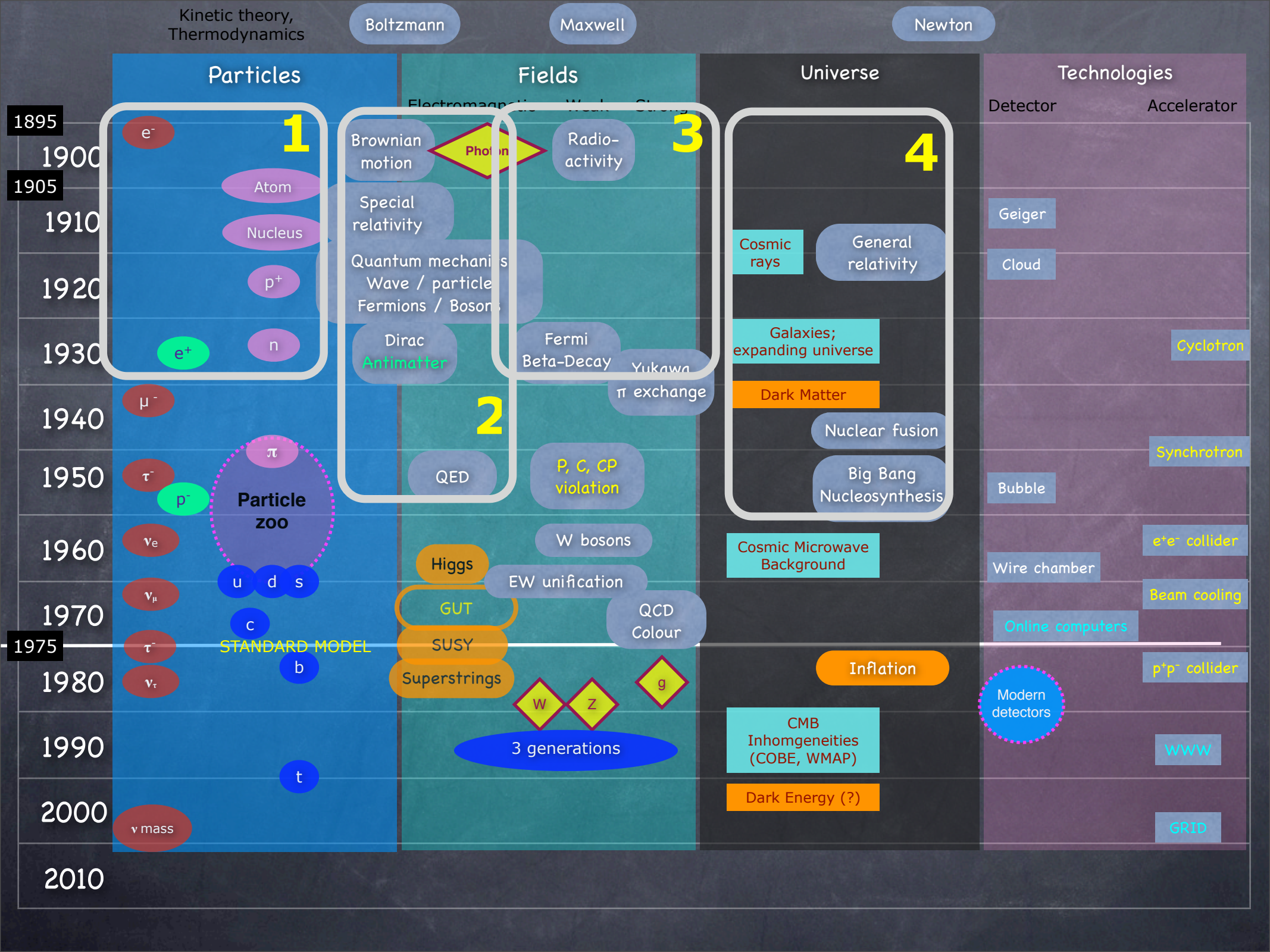
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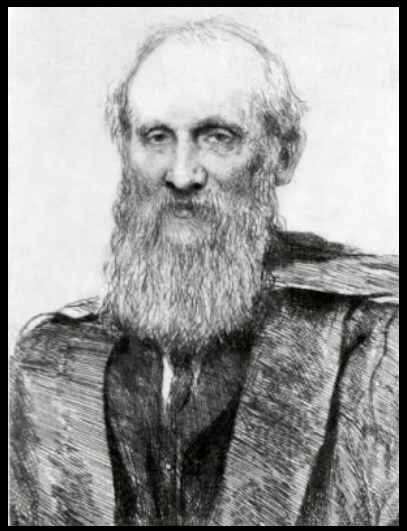


William Thomson
(Lord Kelvin)

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

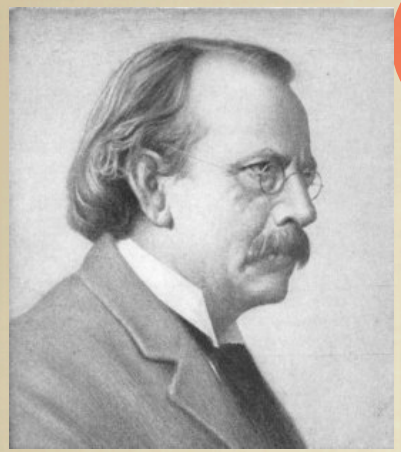
Nothing was known the structure of atoms and nuclei

Only two known fields: gravitation, electromagnetism

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

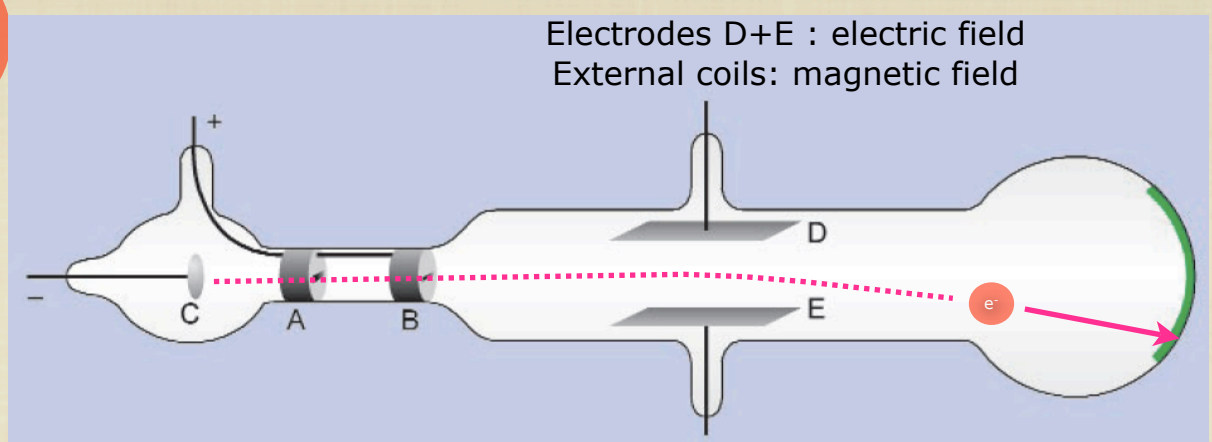
1 PARTICLE SPECTRUM

1897



J.J. Thomson

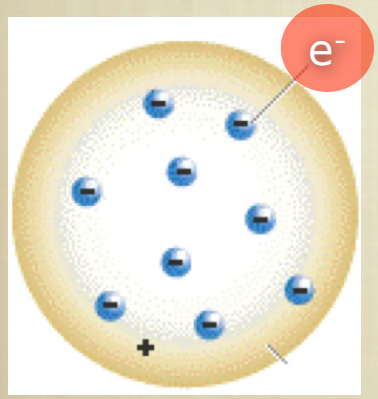
e^-



Cathode ray experiments (~ TV)

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

***later called 'electrons'**



His 'plumpudding' model of the atom (1904)

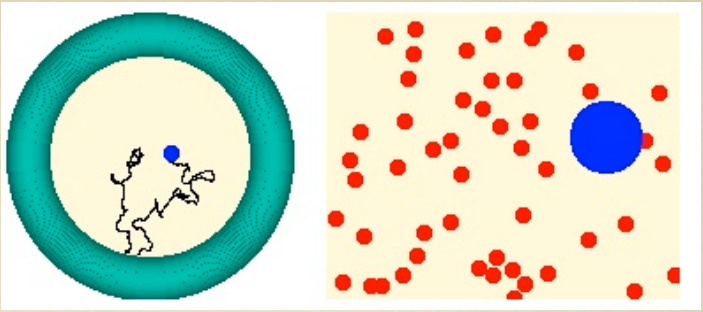
Electrons are sub-atomic particles!

Atom

PARTICLE SPECTRUM

1905

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

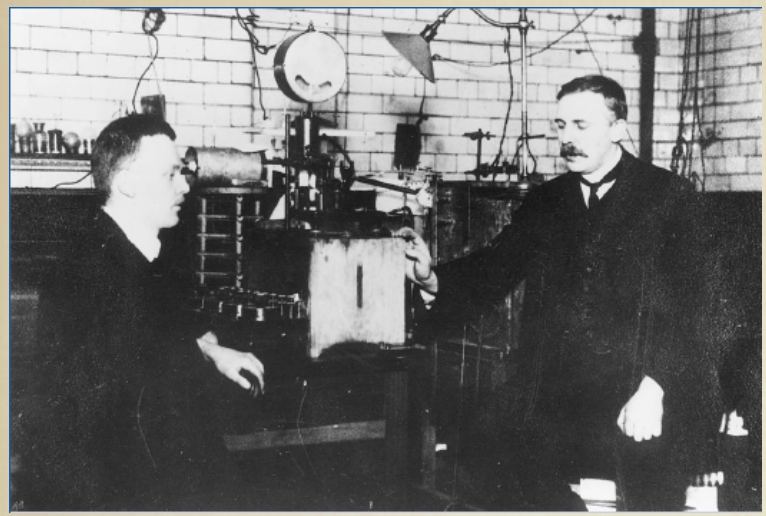
$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$

The existence of atoms was proven

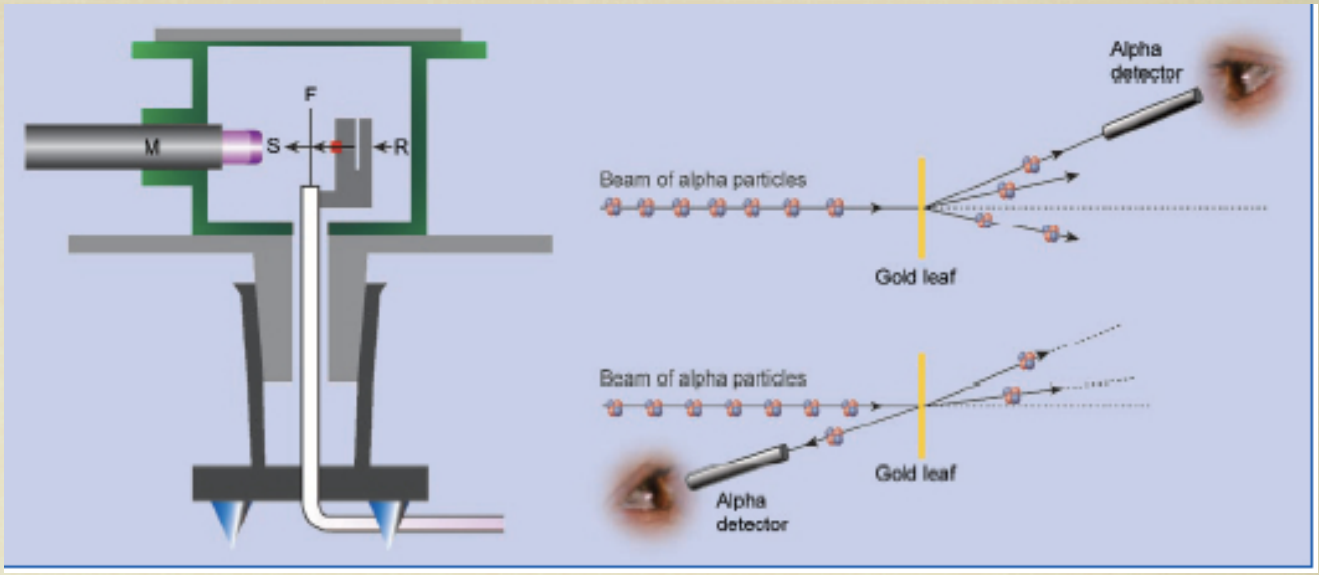
PARTICLE SPECTRUM

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

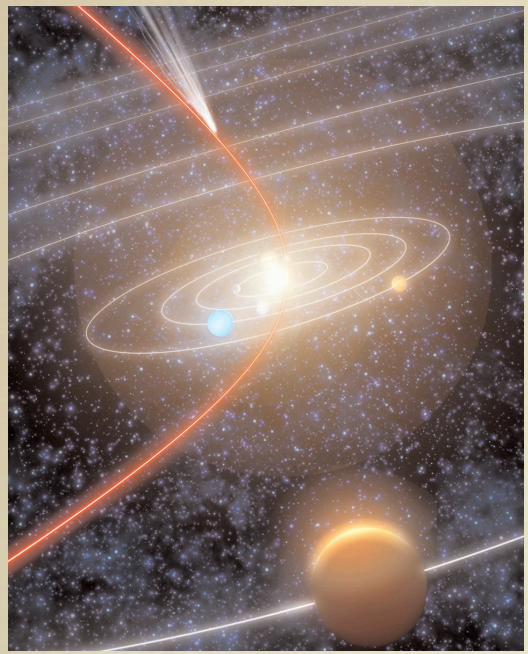
Size: At minimum distance, Coulomb repulsion = kinetic energy: ~ 27 $\times 10^{-15}$ m (true value: 7.3)

Discovery of the nucleus

PARTICLE SPECTRUM

Nucleus

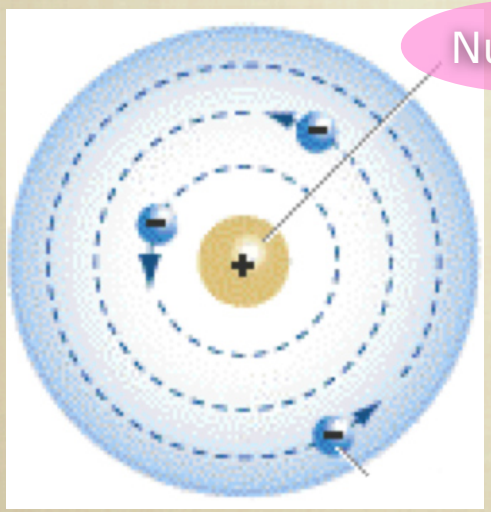
1911



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

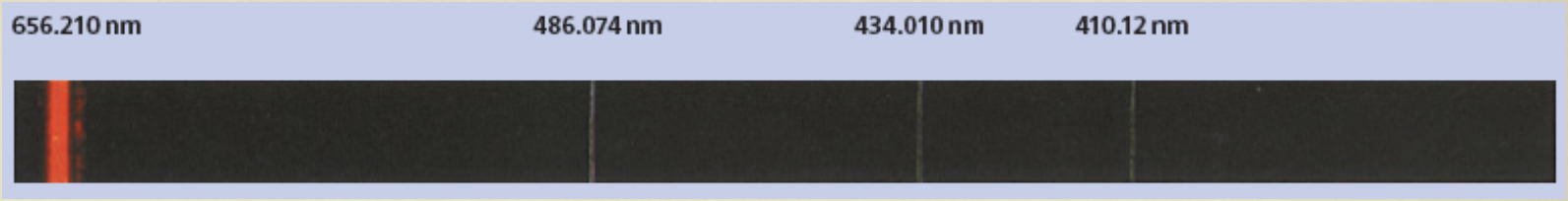
? **How can electrons orbit a nucleus without radiating their energy?**

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

PARTICLE SPECTRUM

1913

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

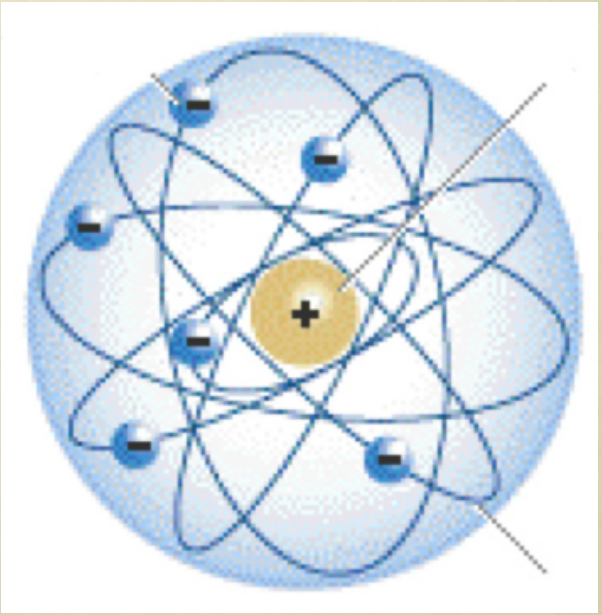


His empirical formula:

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

Niels Bohr visited Rutherford in 1913

he was the first to apply quantum ideas to atoms



- Quantization of angular momentum -> energy levels

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

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

PARTICLE SPECTRUM

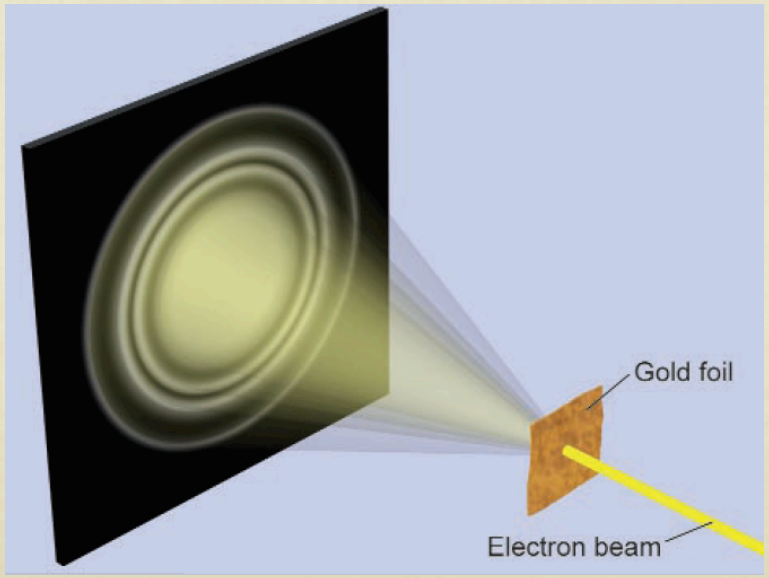
1923-1927

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

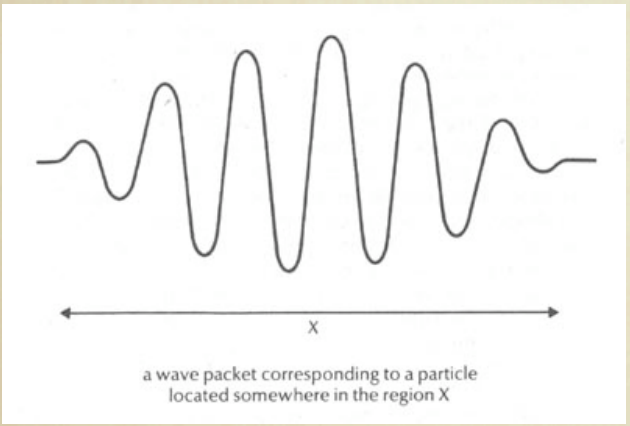
1923-1927

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



Analogy:

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

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

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

PARTICLE SPECTRUM

1923-1927

Schrödinger
1926

Probability wave function

Excellent description
if v << c

If particles are waves -> describe by a wave equation

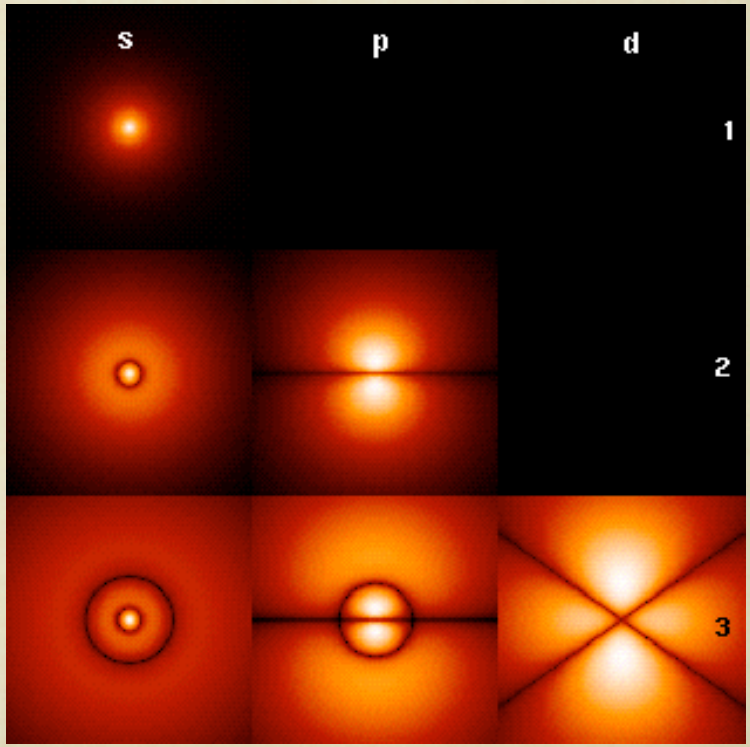
$$H\psi(\mathbf{r},t) = (T+V)\,\psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\psi(\mathbf{r},t) = \mathrm{i}\hbar\frac{\partial\psi}{\partial t}(\mathbf{r},t)$$

Interference: ψ = complex function

Interpretation (Bohr, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability



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

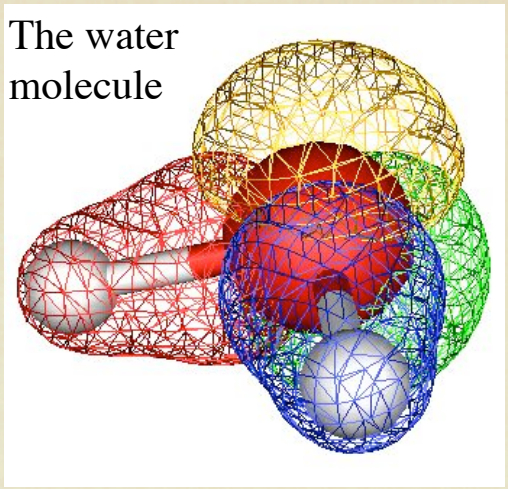
PARTICLE SPECTRUM

1928

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.

PARTICLE SPECTRUM

n

1932

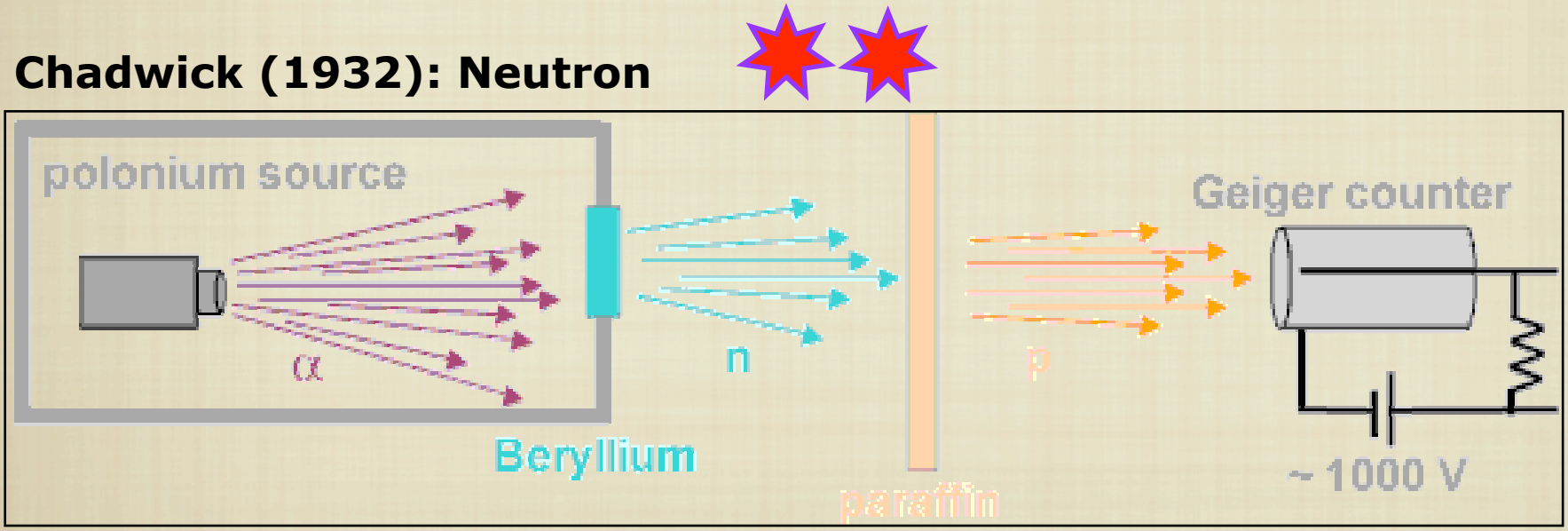
What is the nucleus made of ?

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): Neutron

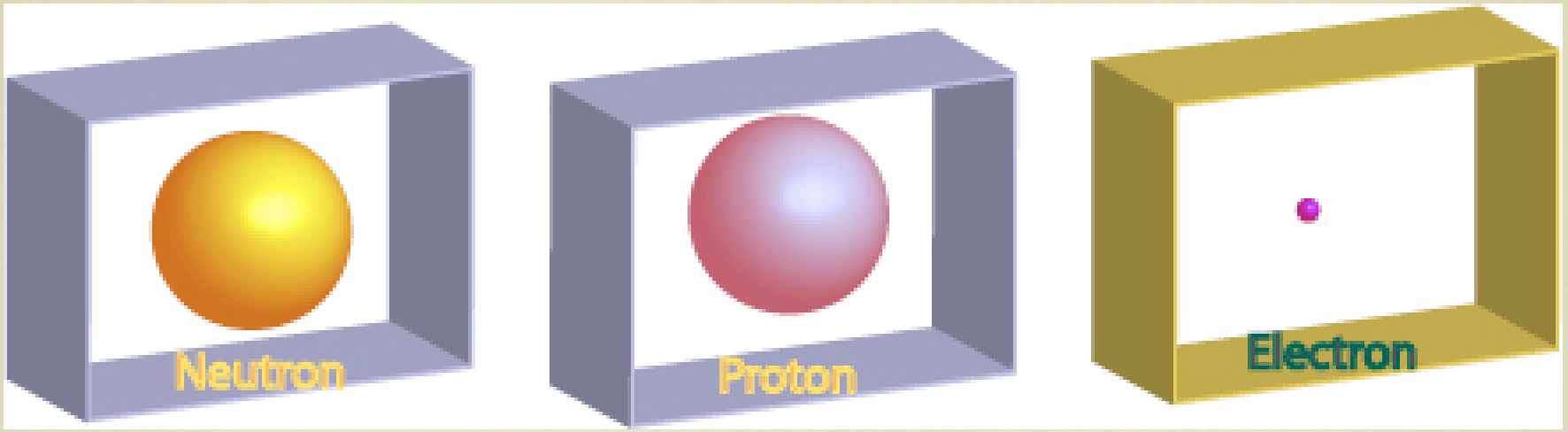


From kinematics: Mass of neutron ~ mass of proton

What keeps everything together? Strong short-range interaction?

PARTICLE SPECTRUM

Fundamental particle spectrum (1932)



2 Fields

1900

What holds atoms and nuclei together?

1900: two fundamental interactions were known:

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

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

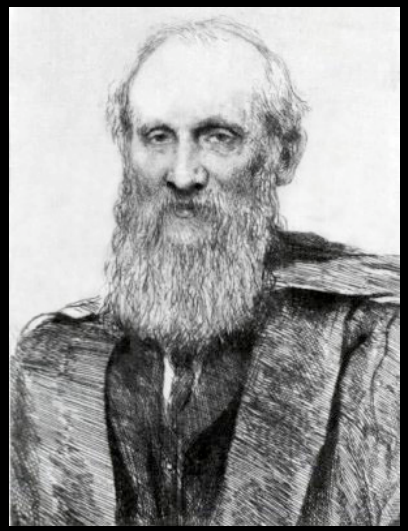
Gravitation

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

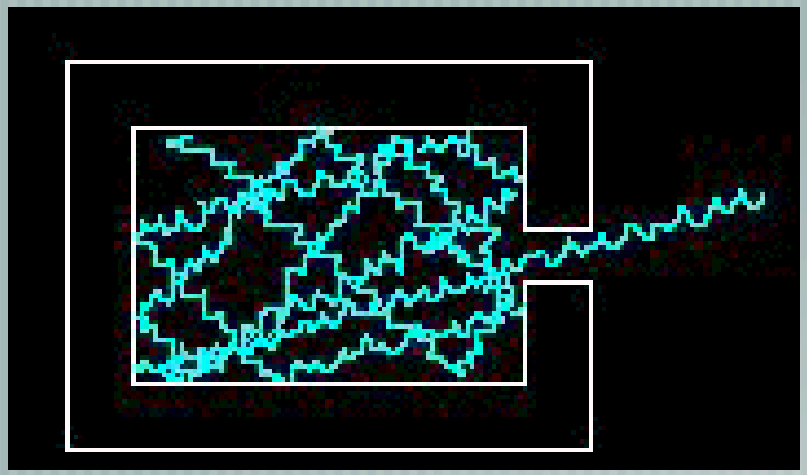
- quantum theory
- relativity

Fields

Photon

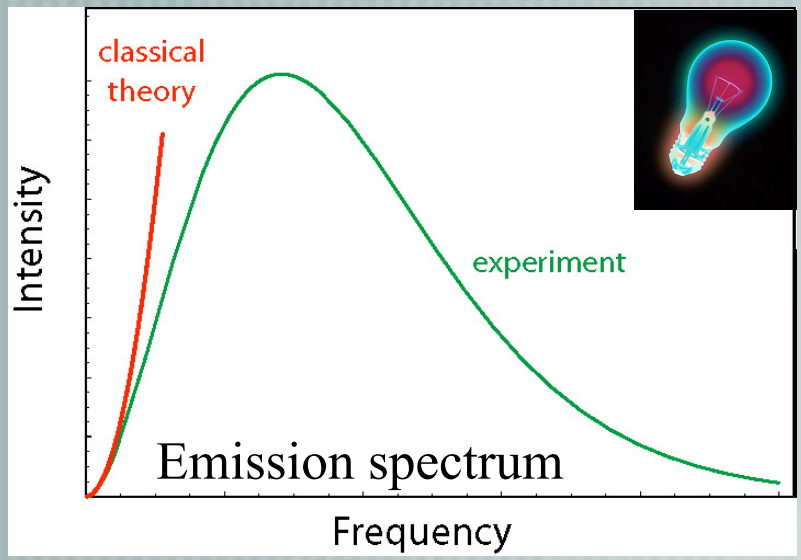
'Electromagnetic' interaction

Blackbody radiation



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

"Radiation function" = f(T) only



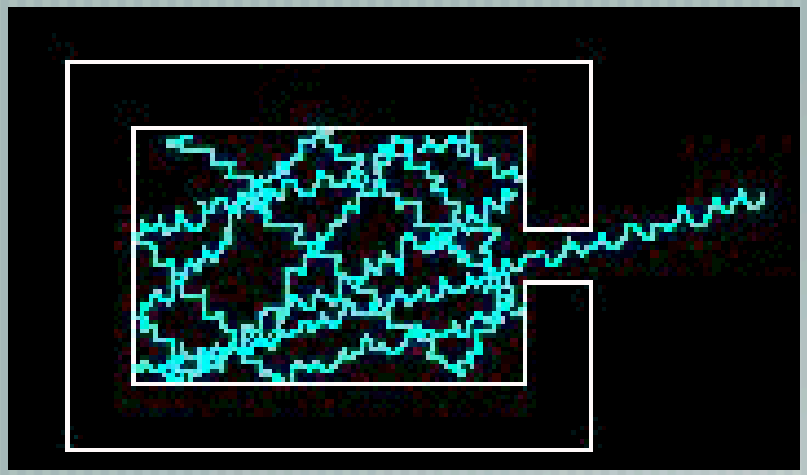
Ok for 'low' temperatures (Jeans law)

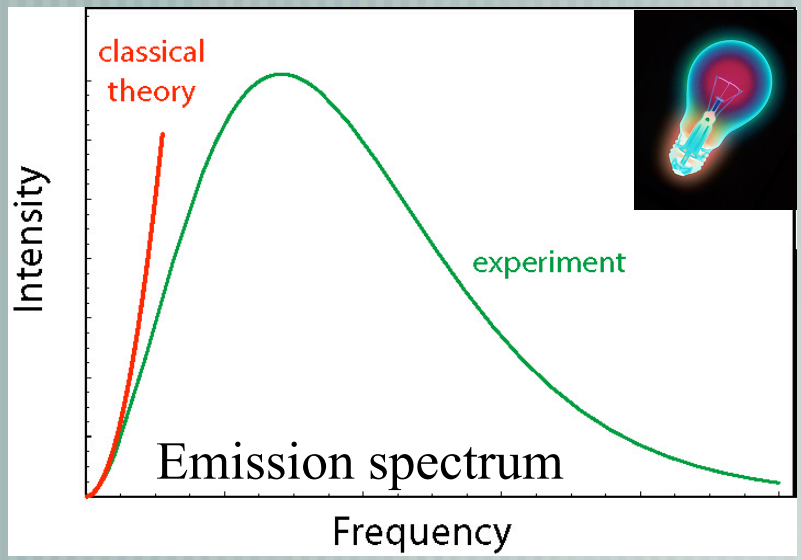
Fields

Photon

'Electromagnetic' interaction

Blackbody radiation





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re-emits thermal equlibrium 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)

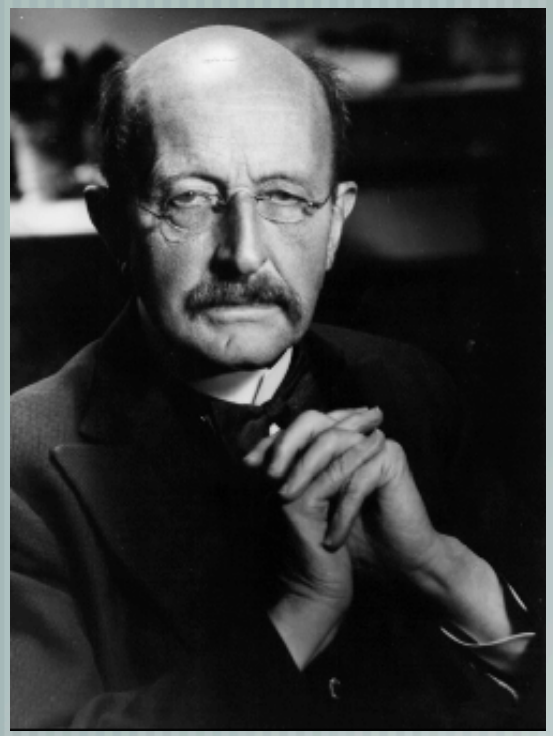
Fields

'Electromagnetic' interaction

Photon

An "Act of Desperation"

14 December 1900



Max Planck

Fields

'Electromagnetic' interaction

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Oscillators (in the wall of the black body)
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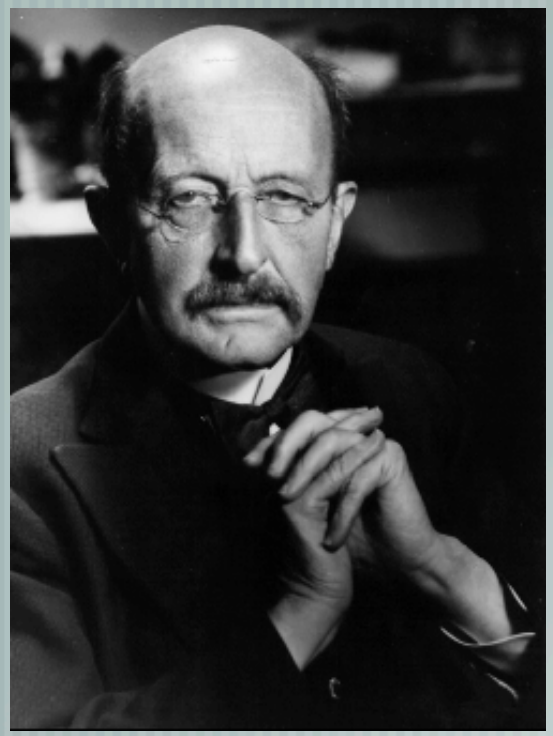

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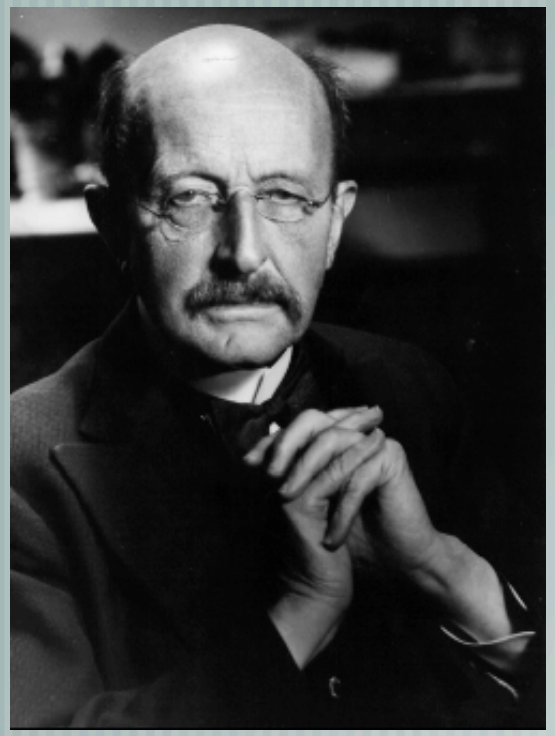

Max Planck

average energy of oscillators

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

Fields

'Electromagnetic' interaction

Photon

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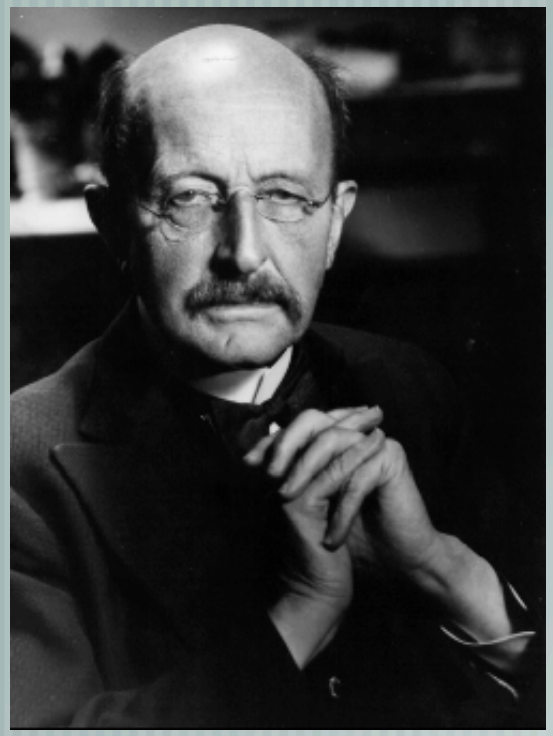


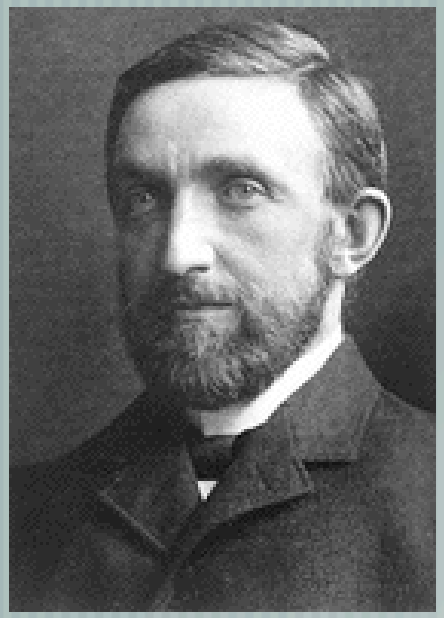
Max Planck

h = new fundamental constant

Photon

1902

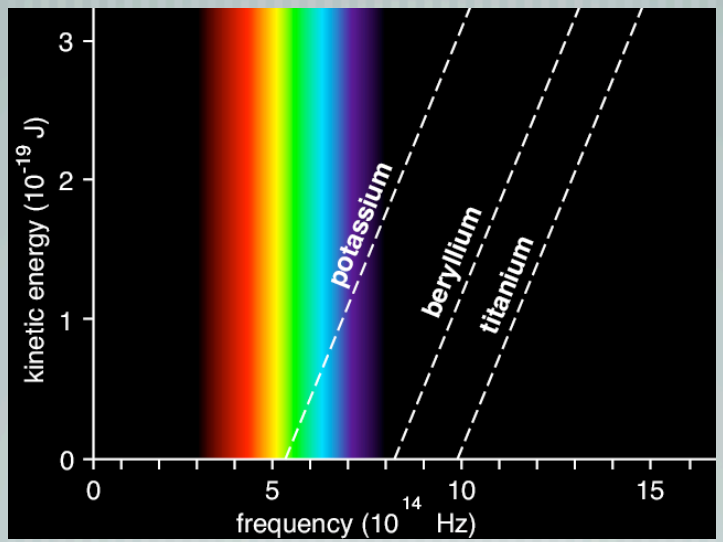
The photoelectric effect



Philipp von Lenard

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")

Photon

1902

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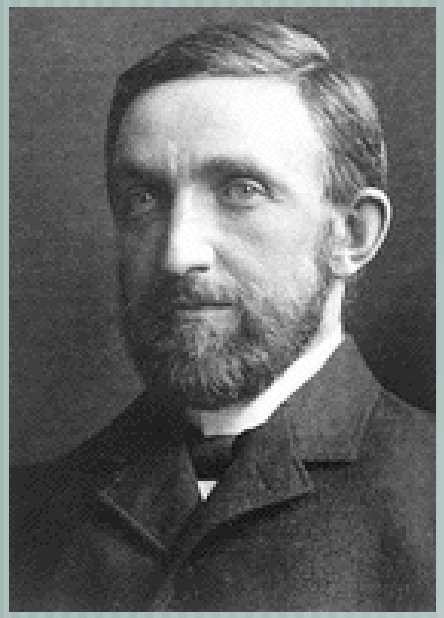

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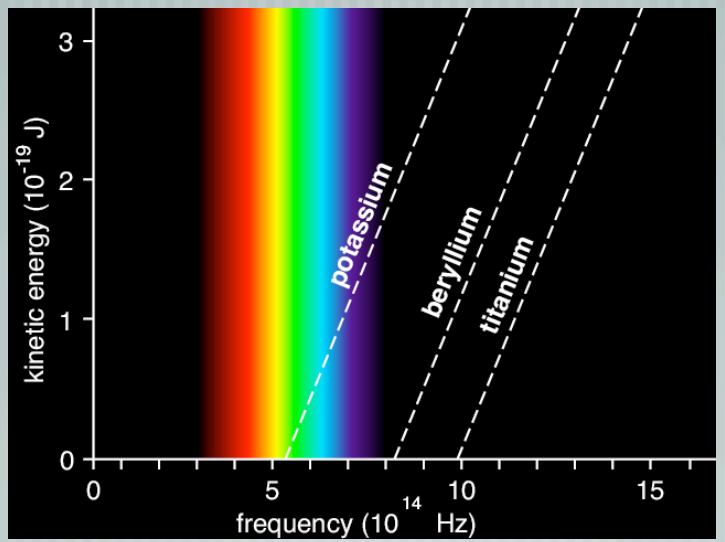

Energy proportional to light **frequency** (slope = "h")

"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

"On a Heuristic Viewpoint Concerning the Production and Transformation of Light"

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

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

"A light quantum gives all its energy to a single electron."

(only proven experimentally by Compton in 1917)

Fields

Reactions to the ‘Light-Quantum Hypothesis’

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Until 1923, Einstein was (almost) the only one to take the light quantum seriously.

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Einstein (1955) ***All these 50 years of pondering have not brought me any closer to answering the question :***
"WHAT ARE LIGHT QUANTA ?"

Special relativity

Einstein had thought about the 'medium' for electromagnetic waves

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

His postulates:

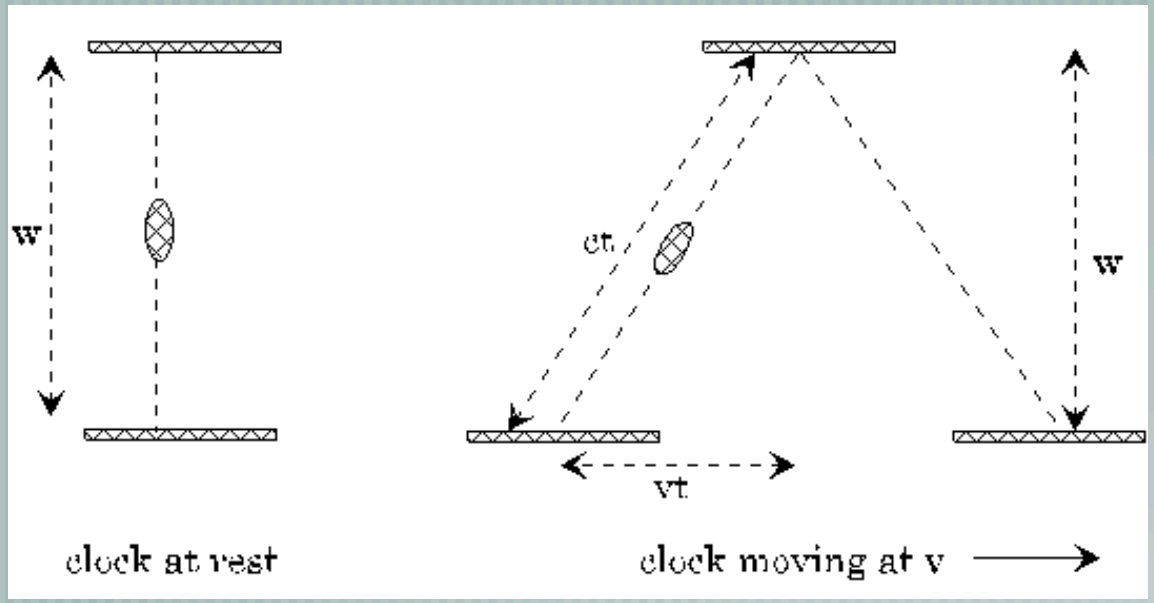
1) Speed of light = constant;
2) all inertial frames are equivalent

His conclusions:

Since c = const, and speed = (space interval/time interval) -->
space and time cannot be absolute!

Fields

Special relativity



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

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

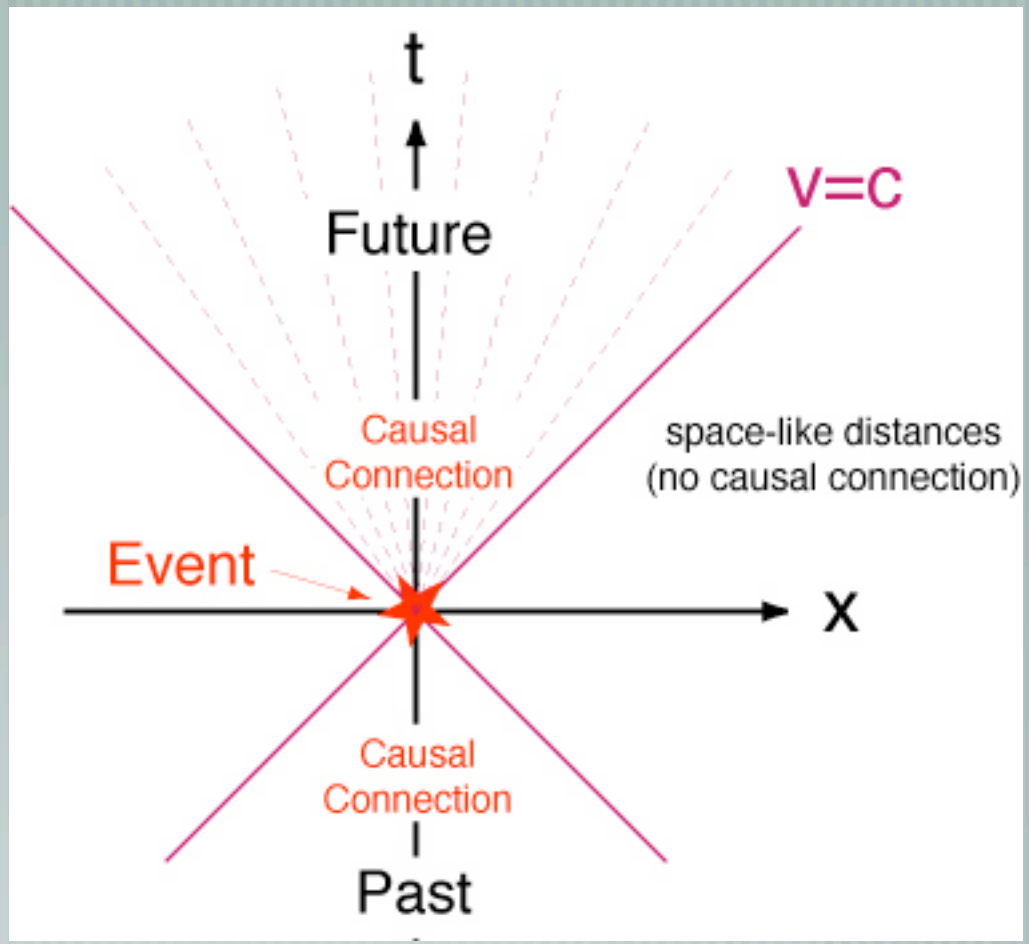
$$t = \frac{w/c}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma \cdot \tau$$

1) Time dilation, space contraction

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

Fields

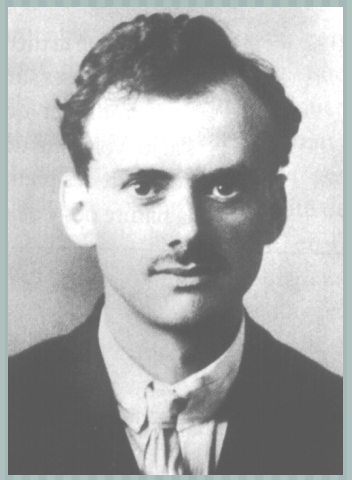
CAUSALITY



Two events can only be in causal connection if their distance is "time-like"

Fields

'Electromagnetic' interaction



Paul A.M. Dirac
(1928)

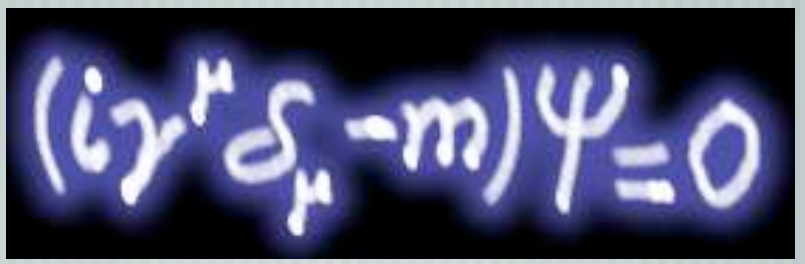
Dirac

Relativity & Quantum Physics

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

'Free' Schrödinger equation -
non-relativistic kinetic energy

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



'Free' Dirac equation -
relativistic energy-momentum

Fields

'Electromagnetic' interaction

Two crucial (theoretical) predictions by Dirac

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

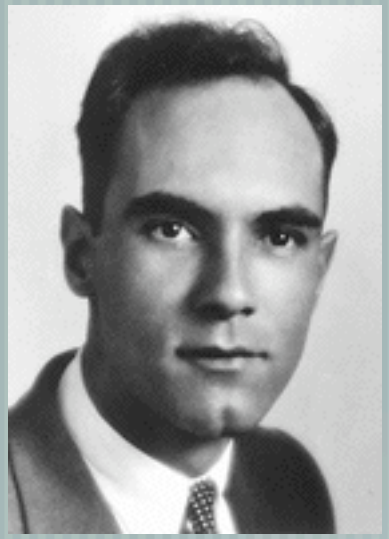
2 components for particle - and 2 components for antiparticle!

Every particle has an antiparticle !

Fields

e^+

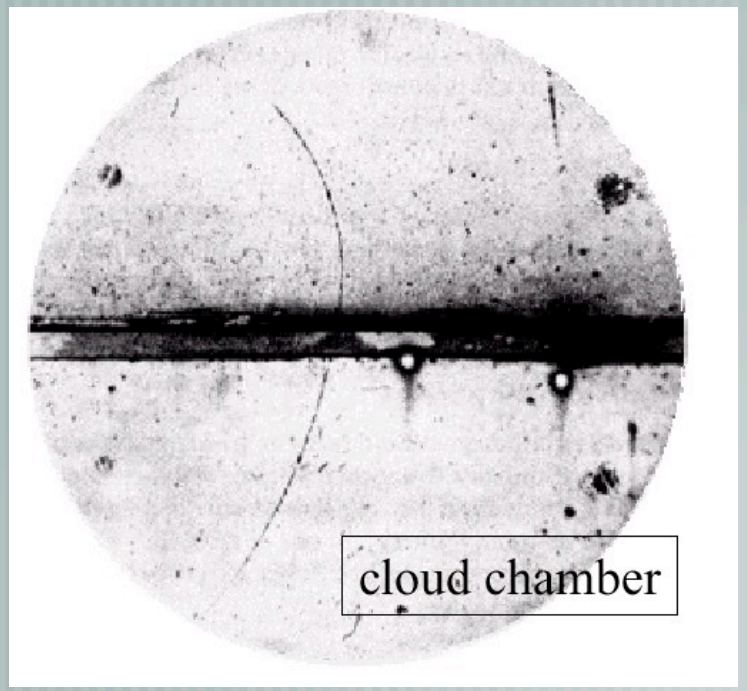
'Electromagnetic' interaction

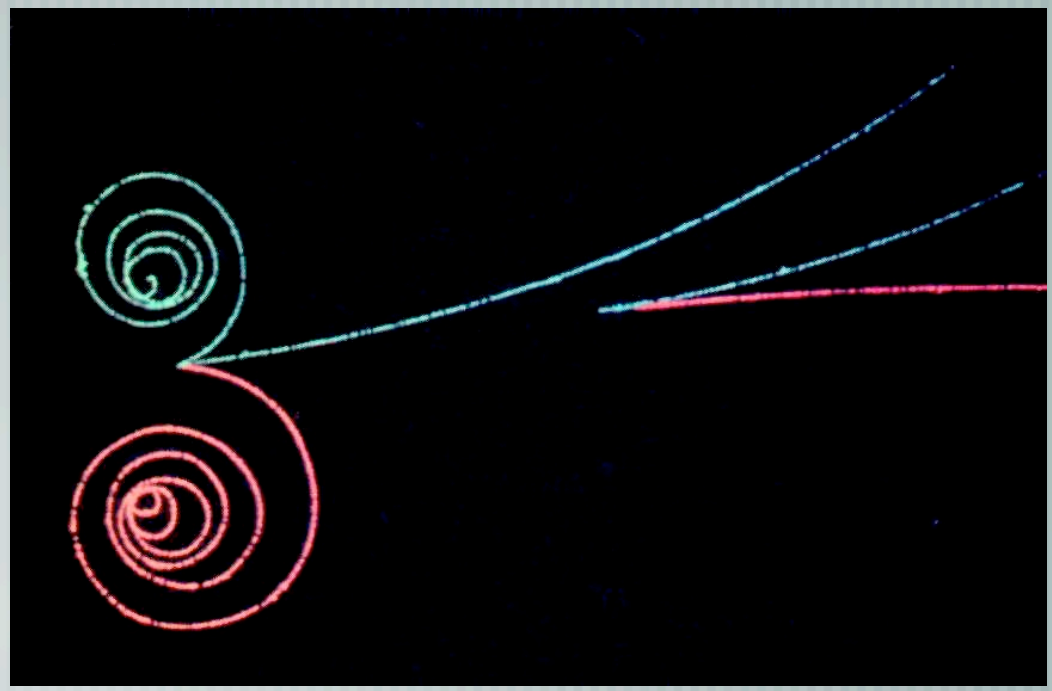


Discovery of the positron

Dirac was right!

Anderson (1932)



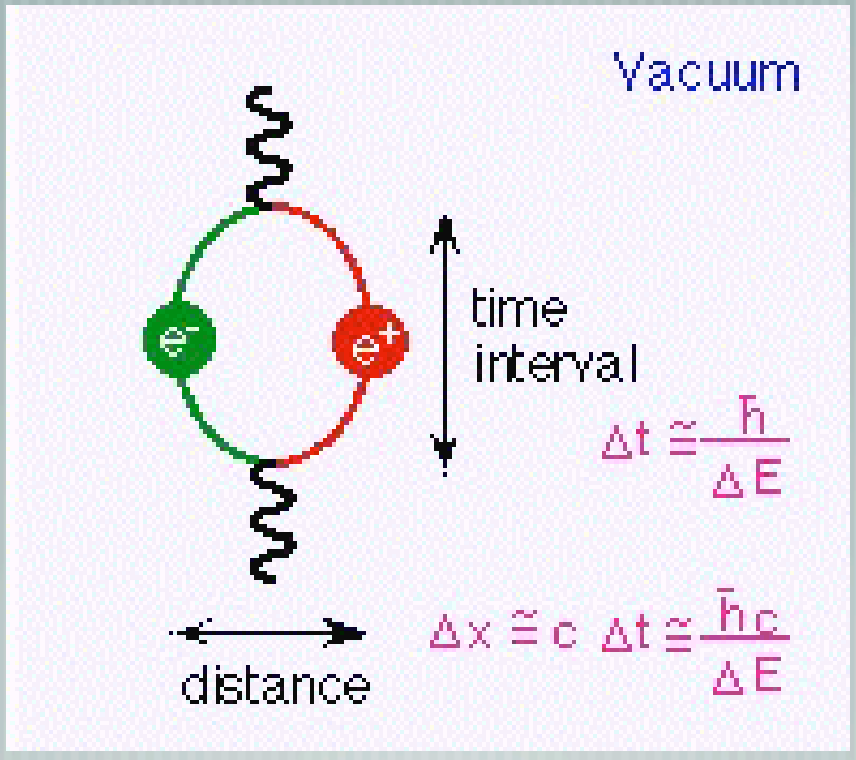


Fields

'Electromagnetic' interaction

Photons & Antiparticles & Quantum Physics =

VACUUM FLUCTUATIONS

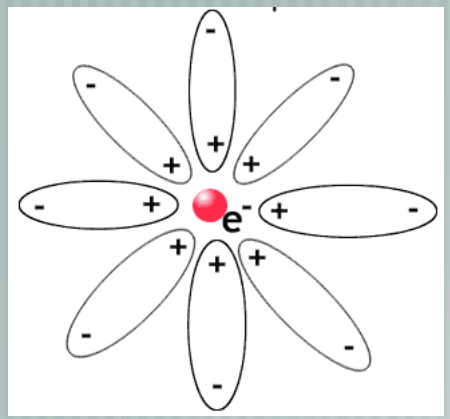


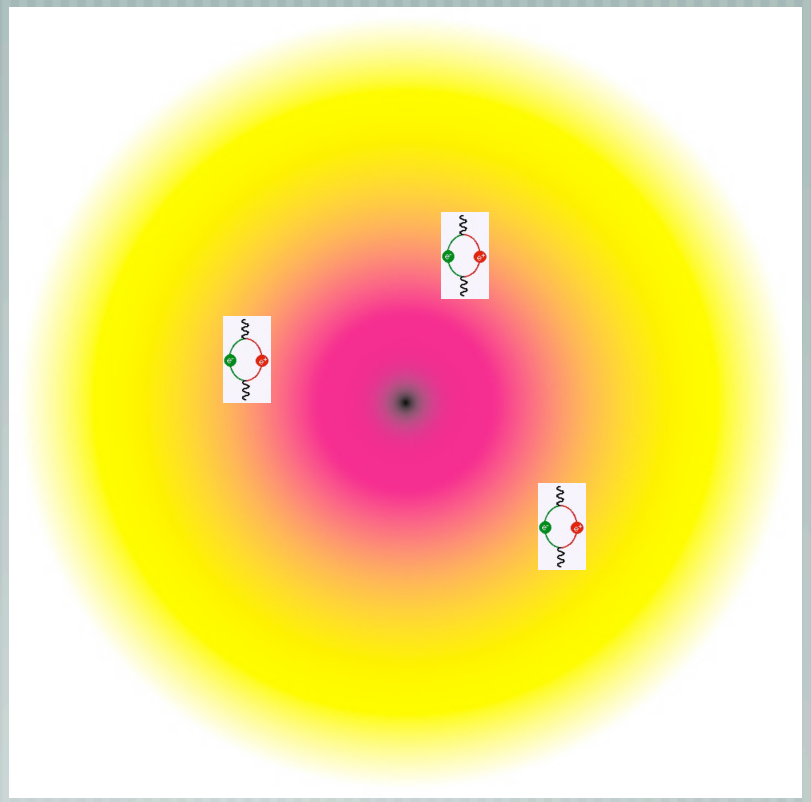
Fields

'Electromagnetic' interaction

How to calculate the interaction of photons and electrons?

a new picture of the electron emerged:

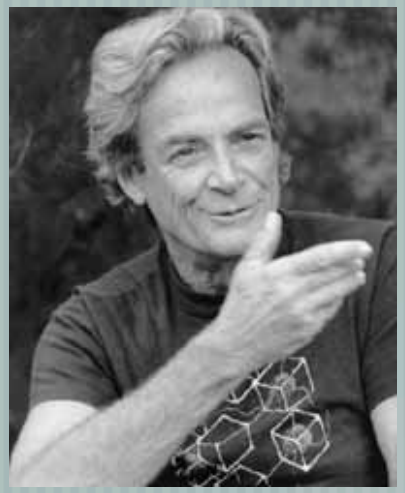




vacuum fluctuations modify its charge and mass ('Debye shielding')

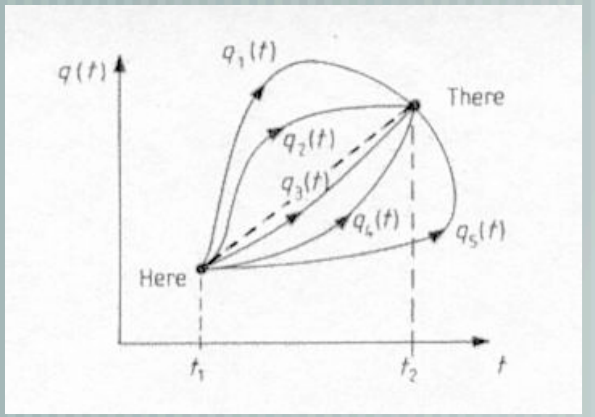
Fields

1934 - 1948



R. P. Feynman

All paths are possible
('multiple slit experiment')



Quantum Electrodynamics

Feynman, Tomonaga, Schwinger

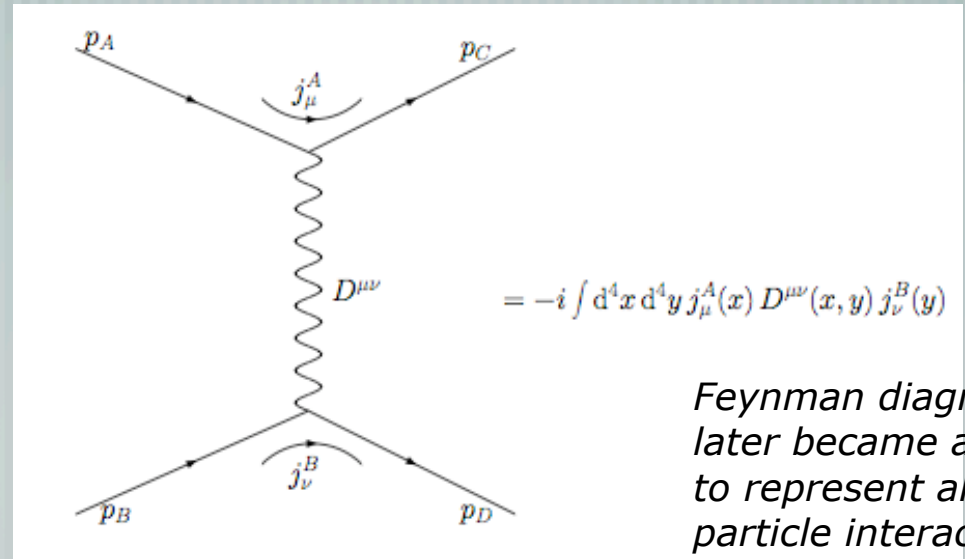
"Renormalization"

The 'naked' electron + vacuum fluctuations = measured electron

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

Feynman diagrams

Precise computation rules - in graphical form



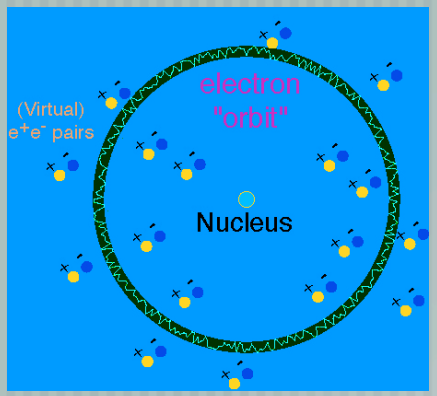
Feynman diagrams later became a graphical way to represent all kinds of particle interactions

Fields

1948

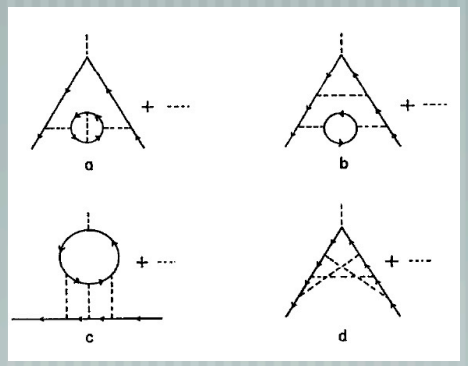
Vacuum fluctuations have observable effects

… and Quantum Electrodynamics allowed to calculate them precisely



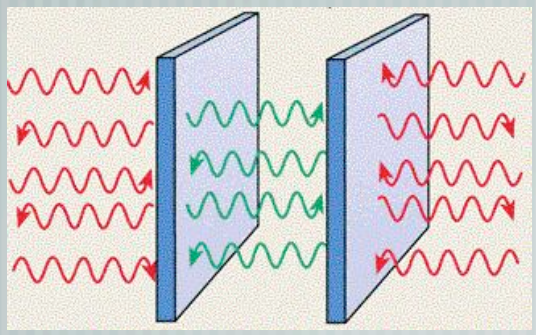
Lamb Shift

(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

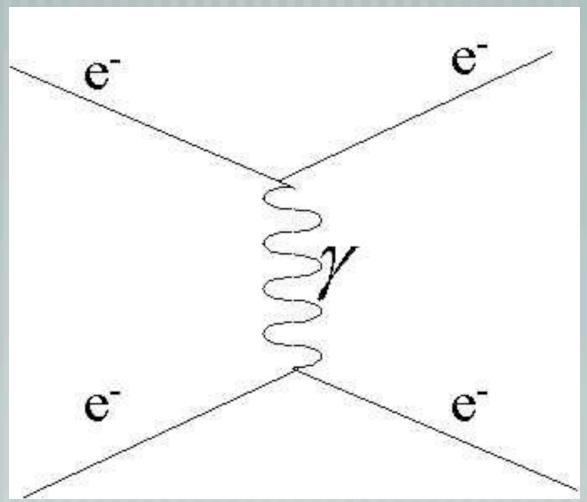
'Electromagnetic' interaction

QED: The interaction of electrons by the exchange of photons

1) Massless virtual photons are continuously emitted by electric charges

2) The $1/r^2$ law comes from the probability to reach other particle at distance r

3) The whole theory can be derived from the principle of 'local gauge invariance'



Could that become a model for other interactions?

Fields

Back to the beginning of the century - another interaction was being discovered

The "Weak Interaction"

1895: Wilhelm Röntgen discovered 'X-rays'

1896: Henri Becquerel discovered radiation from U crystals

1898: Marie and Pierre Curie : ionizing radiation from 'Pechblende' (U + Polonium)

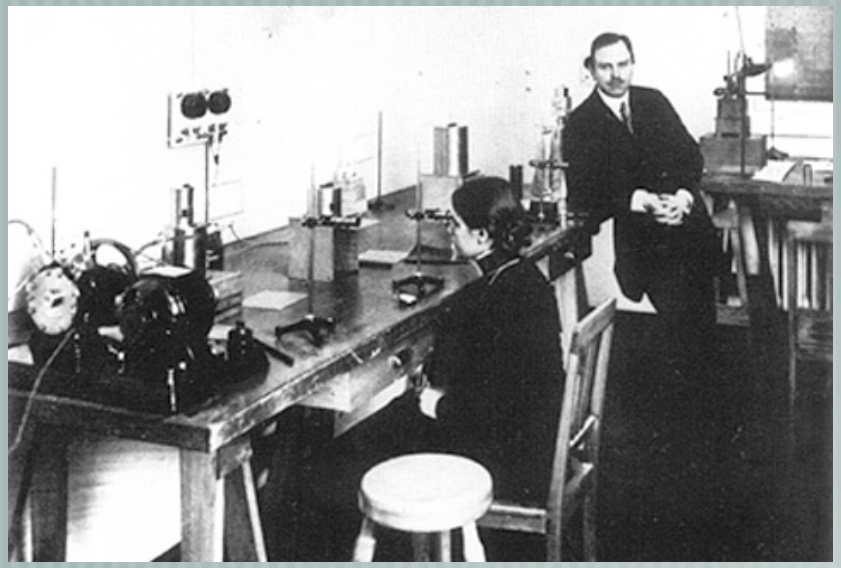
Radioactivity

Fields

'Weak' interaction

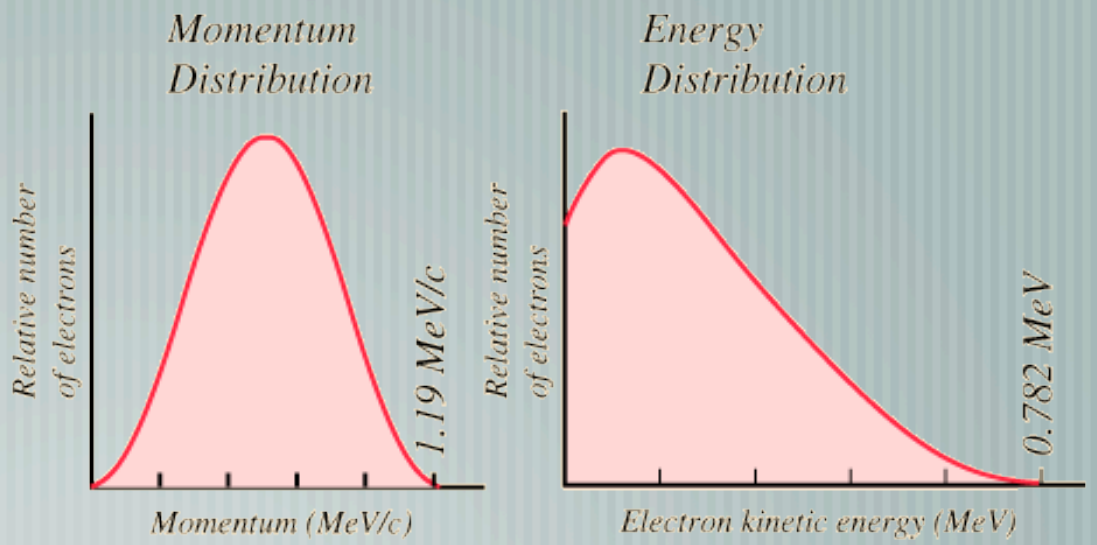
Beta decay of nuclei - electrons emitted with continuous energy spectrum !?

Z --> (Z+1) + e ?



1911 Lise Meitner, Otto Hahn

Violation of energy conservation?



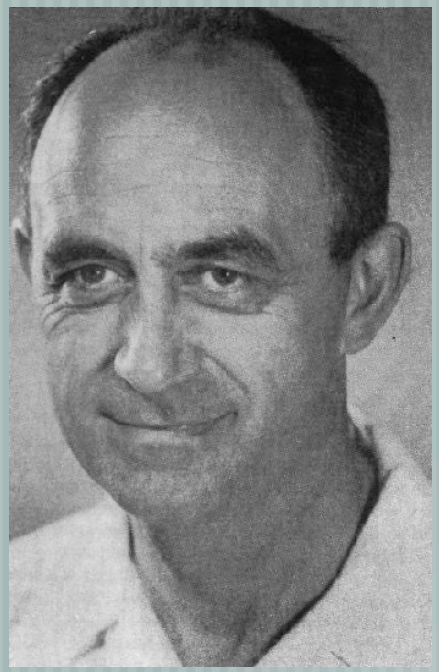
1930 Wolfgang Pauli: an **extremely light neutral particle*** is emitted in beta decay

*'neutron', but in 1931 Fermi called it "'neutrino" (little neutron)

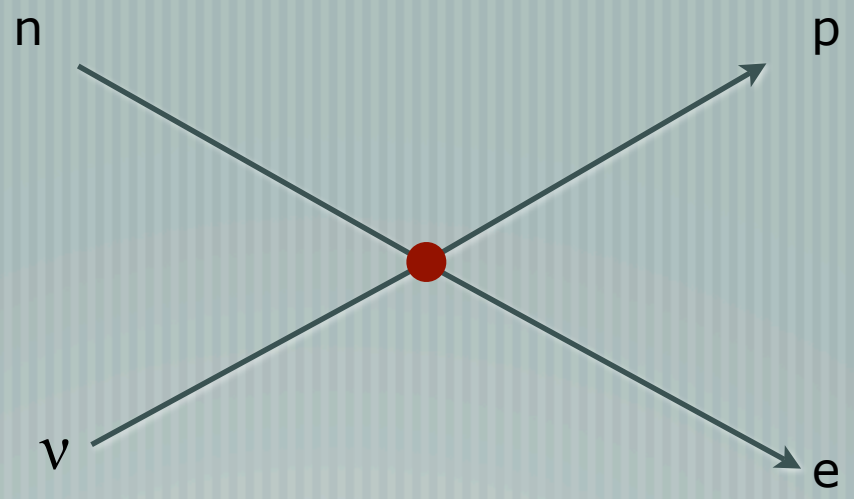
n --> p + e + ν

Fields

'Weak' interaction



Enrico Fermi
(1934)



Proposed a phenomenological model of weak interaction

Point-like coupling with strength $G_F \sim 10^{-5}$ of e.m. interaction

Coupling of two 'currents' (proton-neutron / electron-neutrino)

Ok until ~1960

Fields

'Strong' interaction

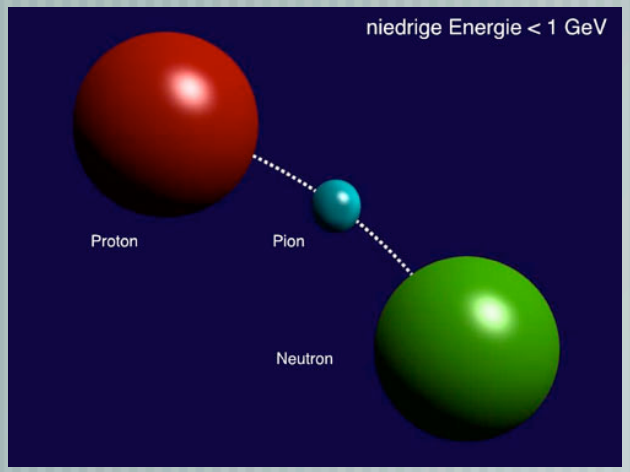
Back to the strong force: keeping protons and neutrons together

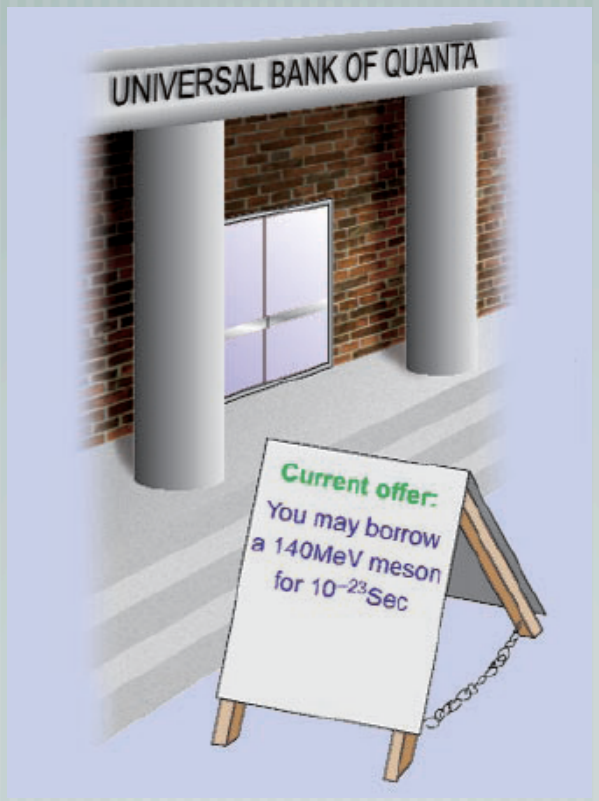
Yukawa (1934)

Exchange of massive particle
Pion

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

Modified Coulomb law



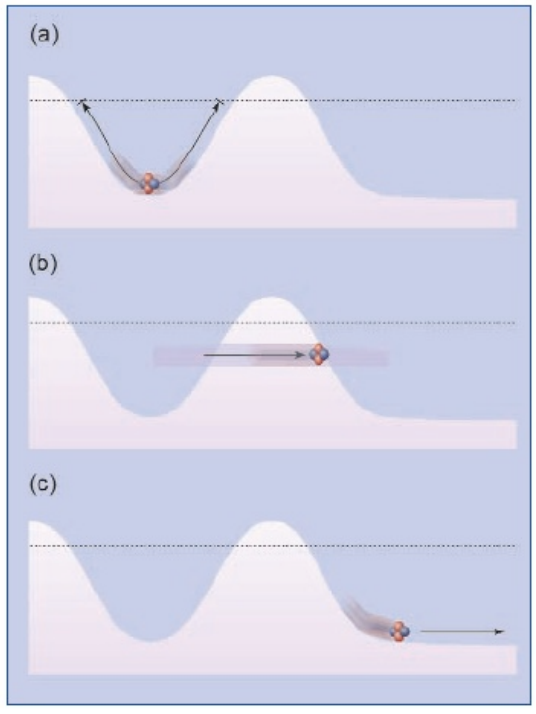


Allowed by uncertainty relation: 1.4 fm ~ 140 MeV

PARTICLE SPECTRUM

1934-1938: decisive breakthroughs in understanding nuclei

George Gamov



Alpha particle (inside the nucleus) have too little energy to get over the top can occasionally tunnel through the well. After tunneling through, the particle accelerates 'down the hill'

Alpha decay:

Alpha particles behave as waves, tunnel through barrier

exponential law

PARTICLE SPECTRUM

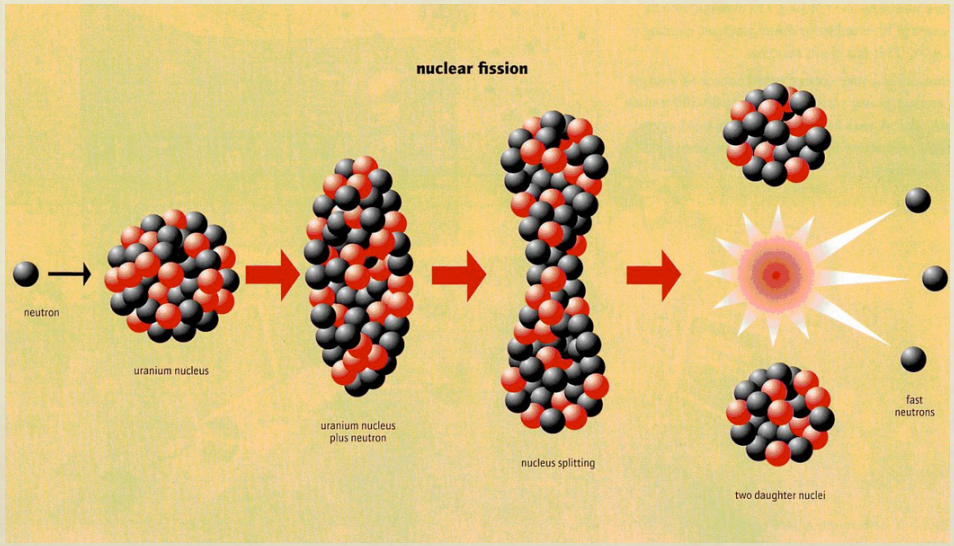
Nuclear Fission

1932: Meitner, Hahn, and Strassmann (another chemist) bombarded heavy nuclei (Uranium) and analyzed the decay products

1938: Lise Meitner had to leave Germany, for Kopenhagen (Bohr)

1938: Hahn and Strassmann found Barium in products of neutron bombardment

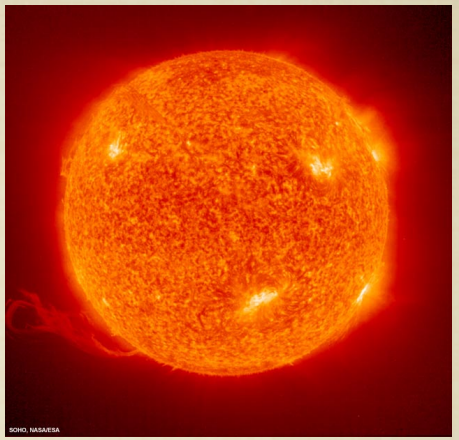
1938: Hahn told Meitner about this discovery. She proved that it must be 'fission', her calculations were based on Bohr's "droplet model" of the nucleus.



Bohr realized the enormous power released by fission.
He quickly informed his colleagues in the US, leading to the Manhattan project.

PARTICLE SPECTRUM

Fusion in stars - strong and weak interaction !



1920: Eddington suggest conversion of mass to energy as the source of solar energy production

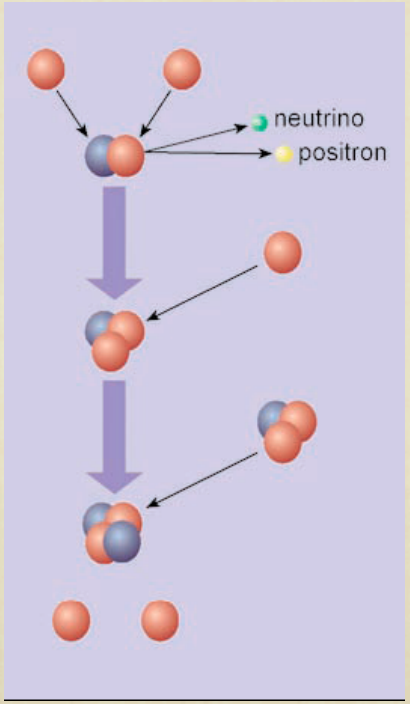
1929: Gamov calculates the 'tunneling factor' of p-p fusion

1939: Hans Bethe article 'Energy production in stars'

Cycle 1: Proton-proton cycle

Cycle 2: C-N-O cycle (v. Weiszäcker)

Hans Bethe



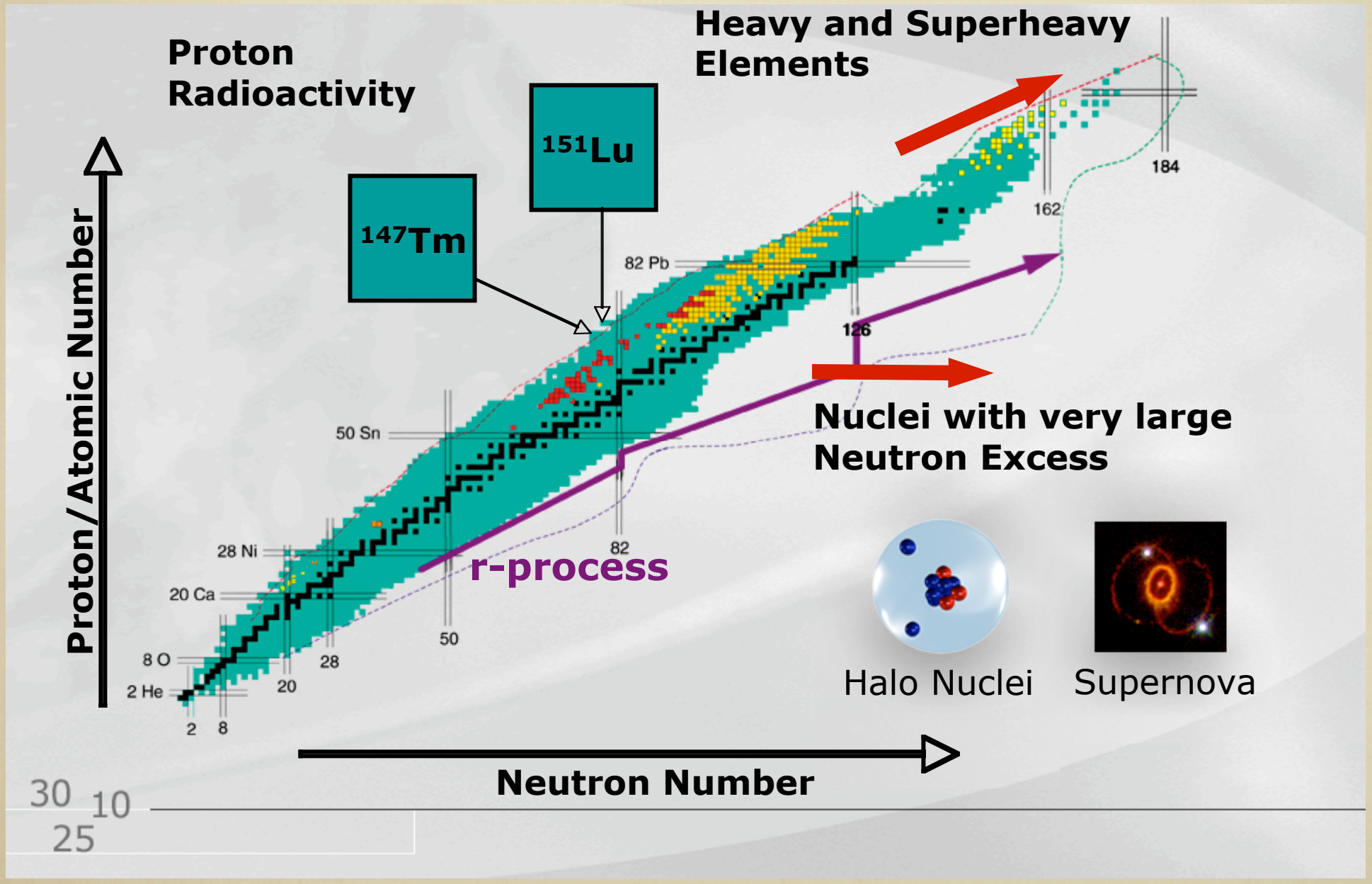
When two protons collide they occasionally tunnel together.

One proton becomes a neutron releasing a neutrino and a positron.

The deuteron formed in this reaction rapidly absorbs another proton yielding a He-3 nucleus,

which reacts with another forming a He-4 nucleus and two protons.

Nuclear Structure



4 The Universe

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Most physicists assumed the Universe to be infinite in space and time.

However, there was a strange observational fact:

It is dark at night.

This could not be explained with an eternal and infinite universe

Universe

1823

Olber’s "Paradox"

1823

Olber's "Paradox"

Heinrich Wilhelm Olbers (1823)

If the universe is endless and uniformly populated with luminous stars,
then every line of sight must eventually terminate at the surface of a star.

Olber's "Paradox"

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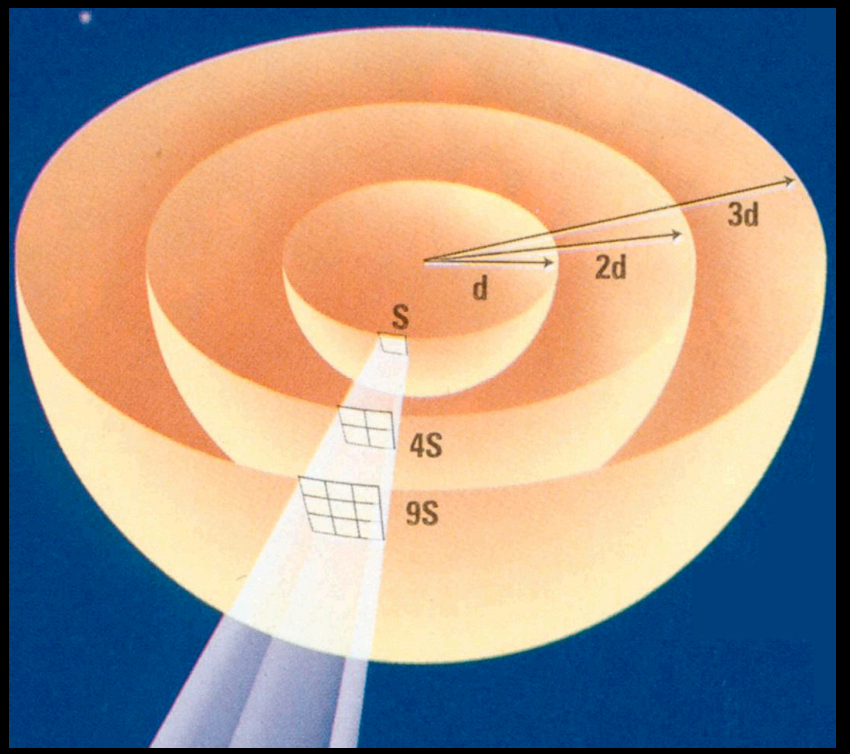
If the universe is endless and uniformly populated with luminous stars,
then every line of sight must eventually terminate at the surface of a star.

Formally:

Each shell contributes ~ r^2
The light decreases with ~$1/r^2$
Light contribution from each shell = constant

Consequence:

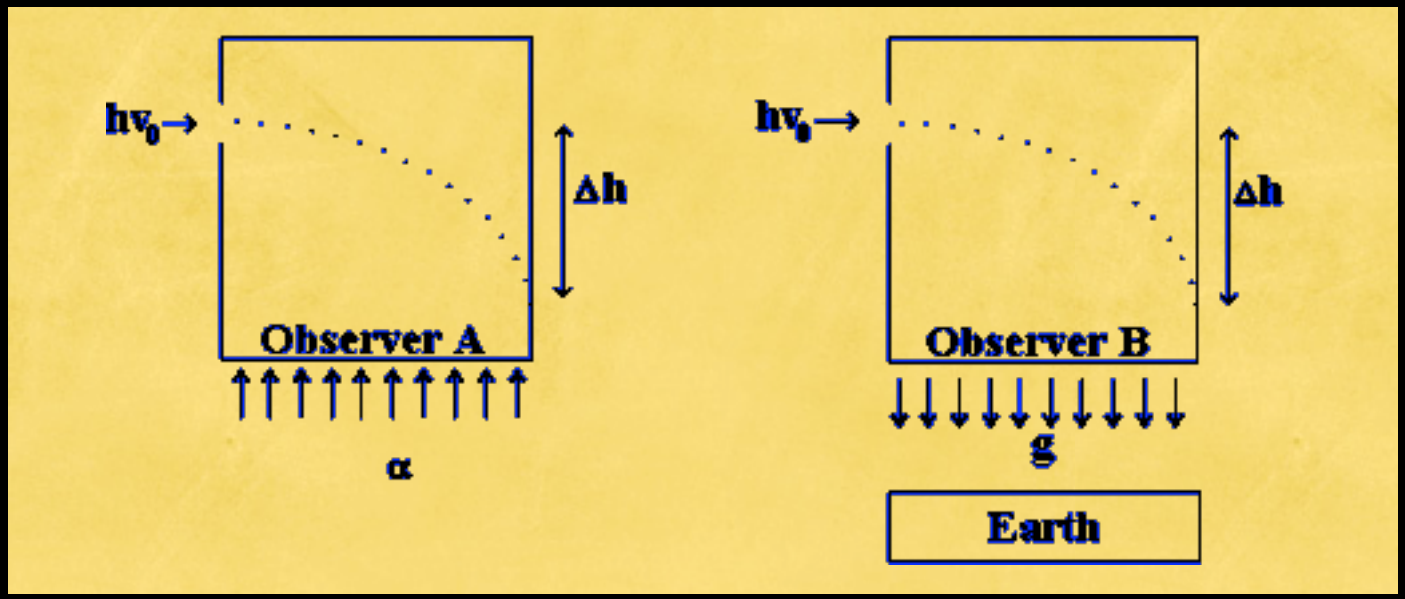
The Universe did not exist forever, or ...
The Universe has a finite size, or ...
Both



Universe

1907

Equivalence Principle



Acceleration (inertial mass) is indistinguishable from gravitation (gravitational mass)

"The happiest thought of my life" (Albert Einstein)

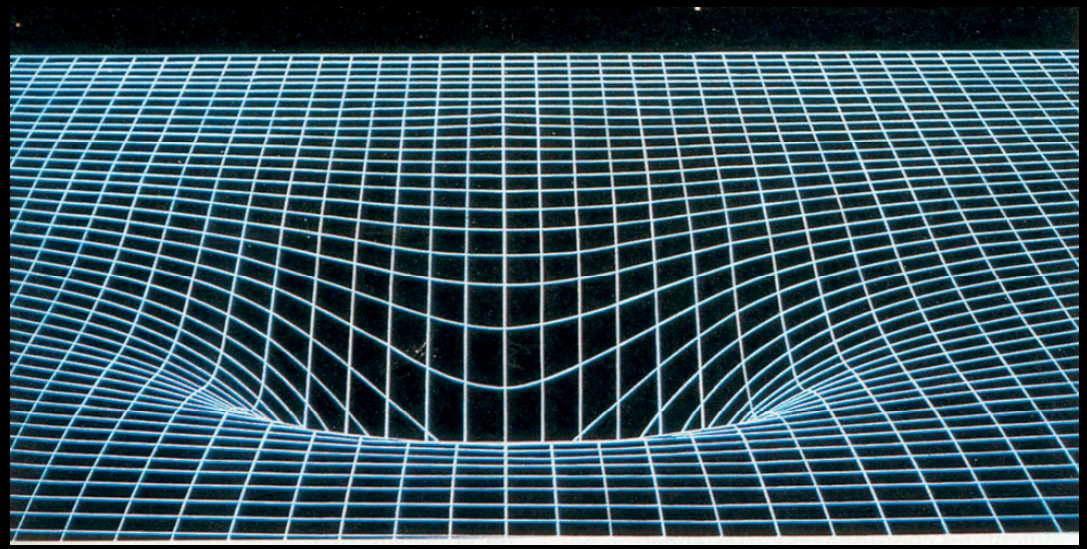
Universe

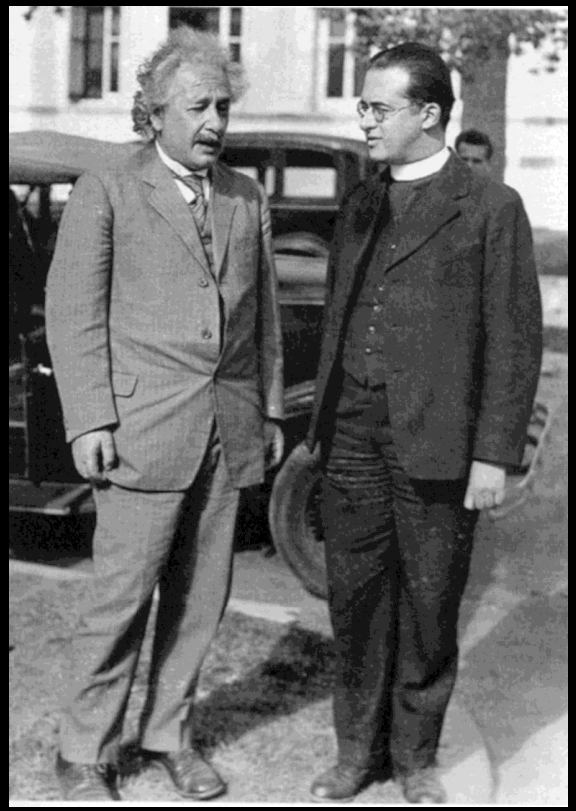
1915

Light rays define the shortest path in space.
Accelerated elevator: light follows follows a parabolic path
Gravitational field: light path must be bent !
Space and time must be curved

Albert Einstein (1912-15) : General Relativity

Matter tells Space how to curve
Space tells Matter how to move





George Lemaitre (1927)

The whole Universe expands
A ‘hot primordial atom’ ?

Universe

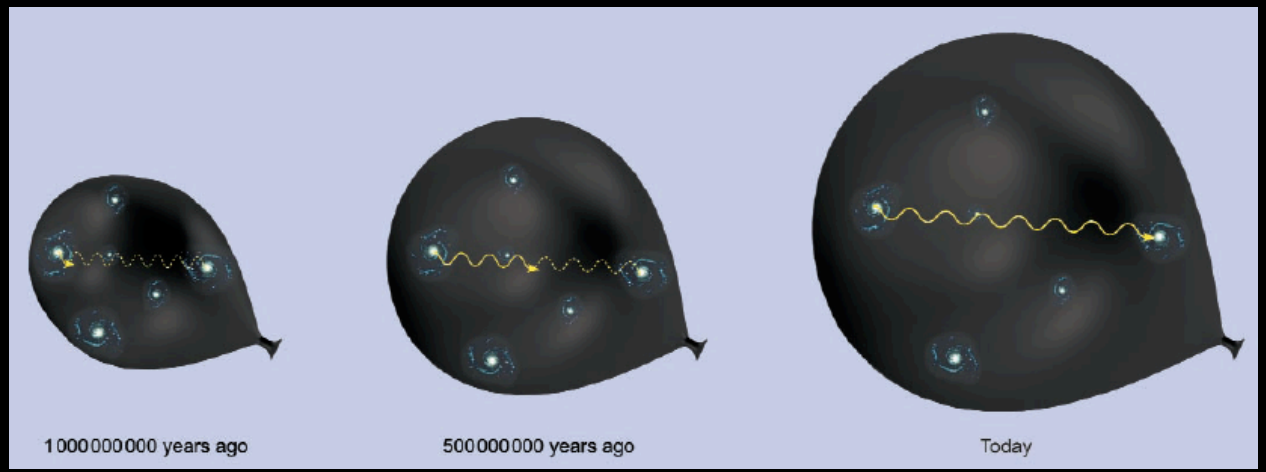
1915

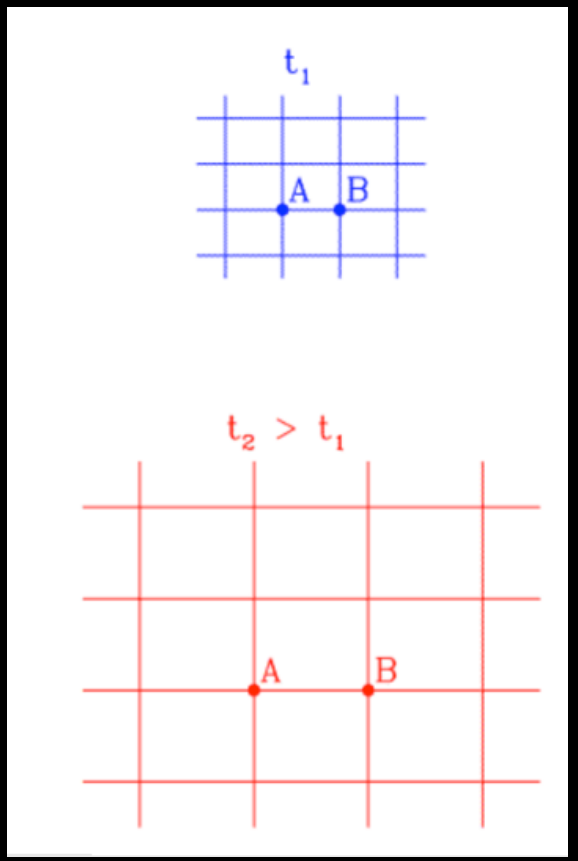
Friedmann described the expansion of the Universe using a scale factor a(t)

$$r_{AB}(t) = a(t)x_{AB}$$

His equation relates the average energy density "ρ" and the curvature factor K with the expansion rate

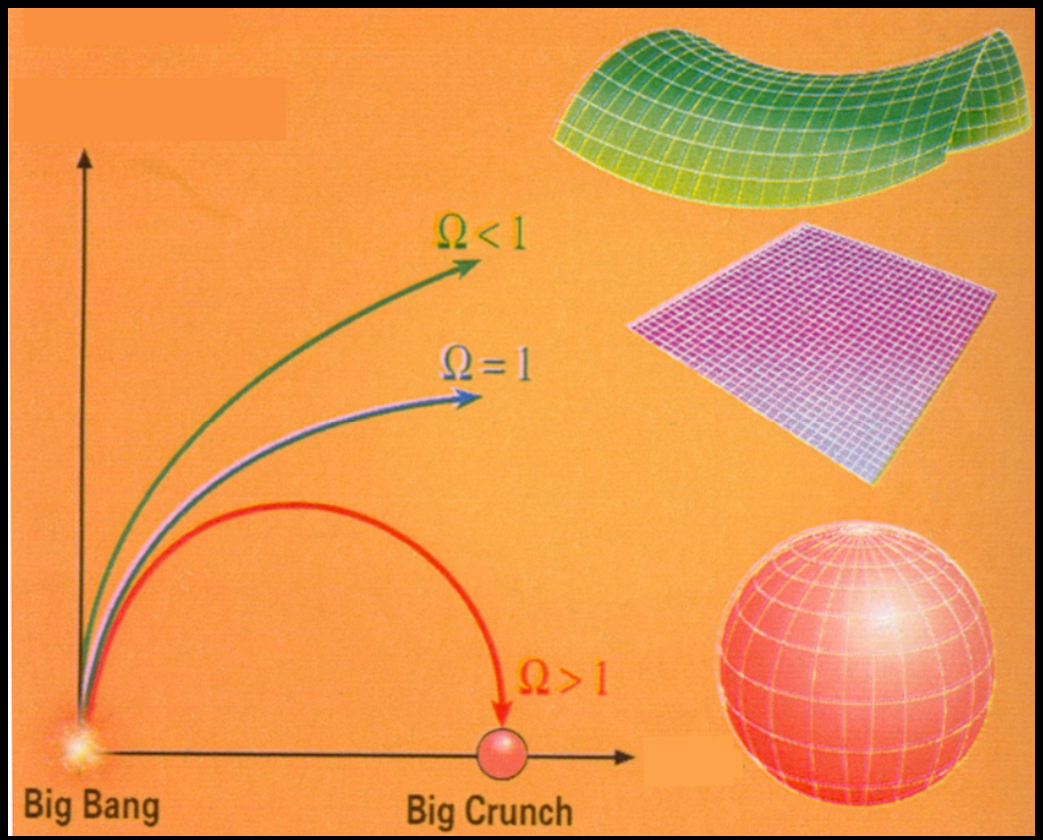
$$(\frac{1}{a}\frac{da}{dt})^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{K}{a^2}$$



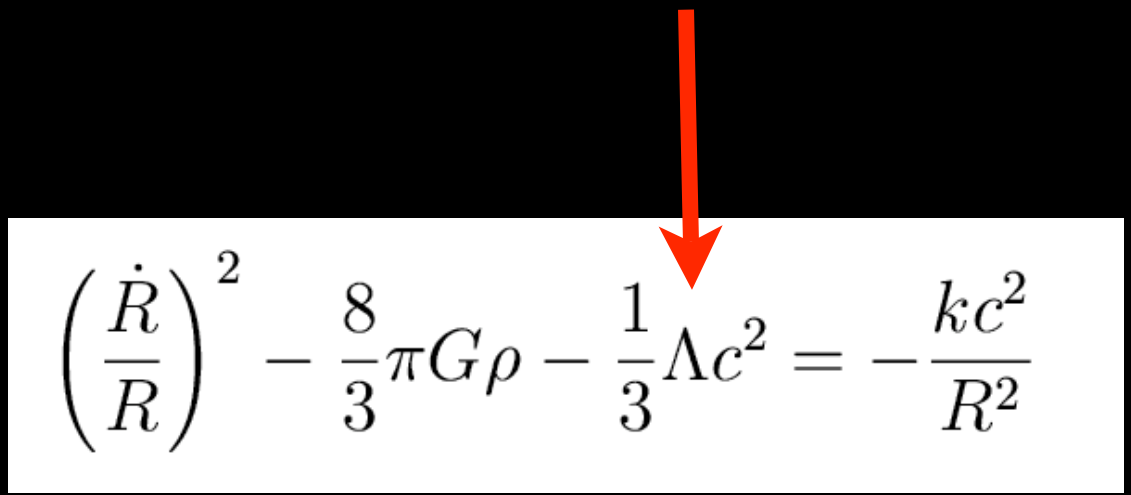


Universe

The crucial question was the mass of the Universe. In principle, it could be anything. However - there is a 'critical energy density'.
If the average energy density is larger, the Universe will stop expanding and fall back into a big crunch one day ('deceleration' parameter)



Universe

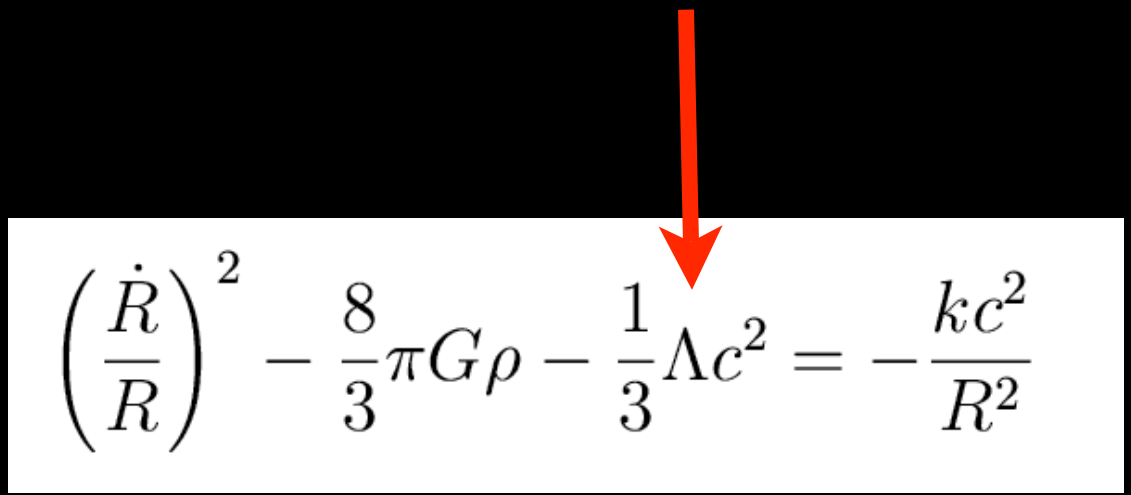


$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2 = -\frac{kc^2}{R^2}$$

Universe

Einstein did not like the idea of a 'dynamic' Universe.

He believed in an eternal and static Universe.



$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2 = -\frac{kc^2}{R^2}$$

Universe

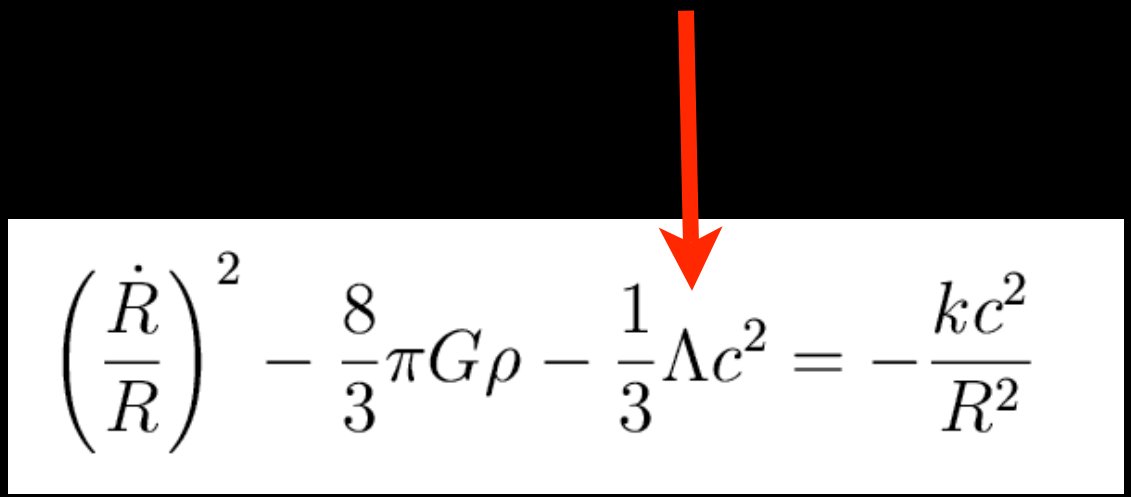
Einstein did not like the idea of a 'dynamic' Universe.

He believed in an eternal and static Universe.

But his own equations predicted something else.

Therefore he decided to tinker with them, by adding a term named

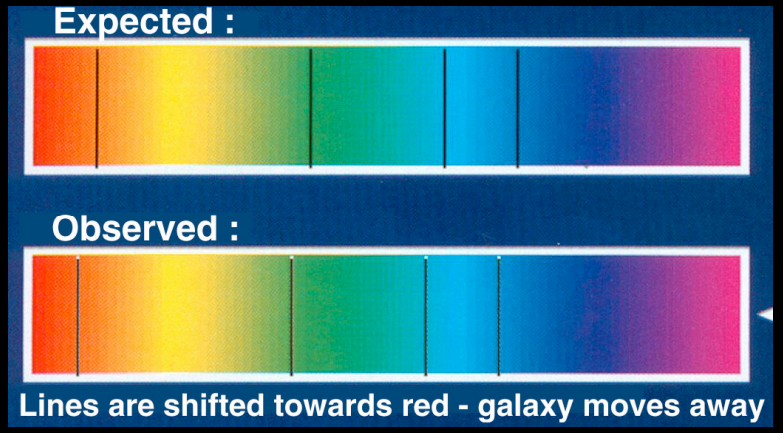
'cosmological constant'

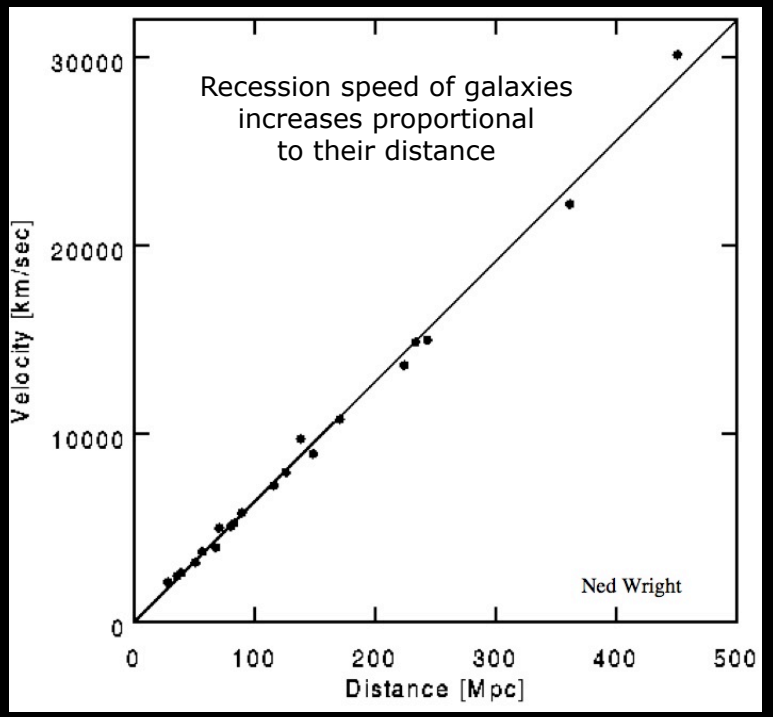


$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2 = -\frac{kc^2}{R^2}$$

Universe

Edwin Hubble (1929)
Mt. Palomar telescope





Einstein concedes: cosmological constant 'my biggest blunder'

Universe

Observation of many stars and galaxies revealed an amazing fact:

The Universe is the same in every direction, at any distance ...

Hydrogen ~ 75 %
Helium-4 ~ 25 %
He-3 ~ 0.003 %
Deuterium ~ 0.003 %
Li-7 ~ 0.00000002 %

There must be a reason ...

Universe

1948

1948: The 'Big Bang' model* of the beginning of the Universe

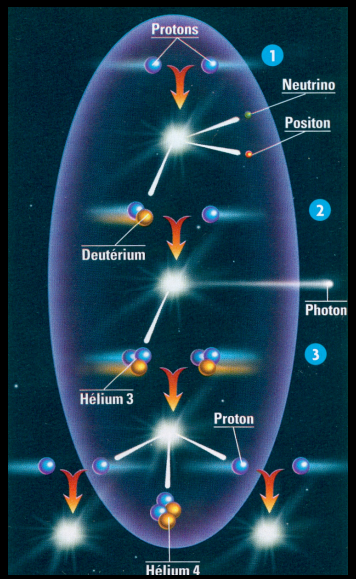
George Gamov

The Universe started from an extremely hot initial state

Then it expanded rapidly, while cooling down

In very early times, the Universe was mostly radiation

Radiation produced particles (protons, neutrons, electrons)



- In the first few minutes, there was just enough time to create the lightest elements
- There should be an 'echo' in form of a uniform black-body radiation (T ~ 5 K)

* The name 'Big Bang' was used by Fred Hoyle to ridicule Gamov's idea. Later Fred Hoyle was ridiculed.