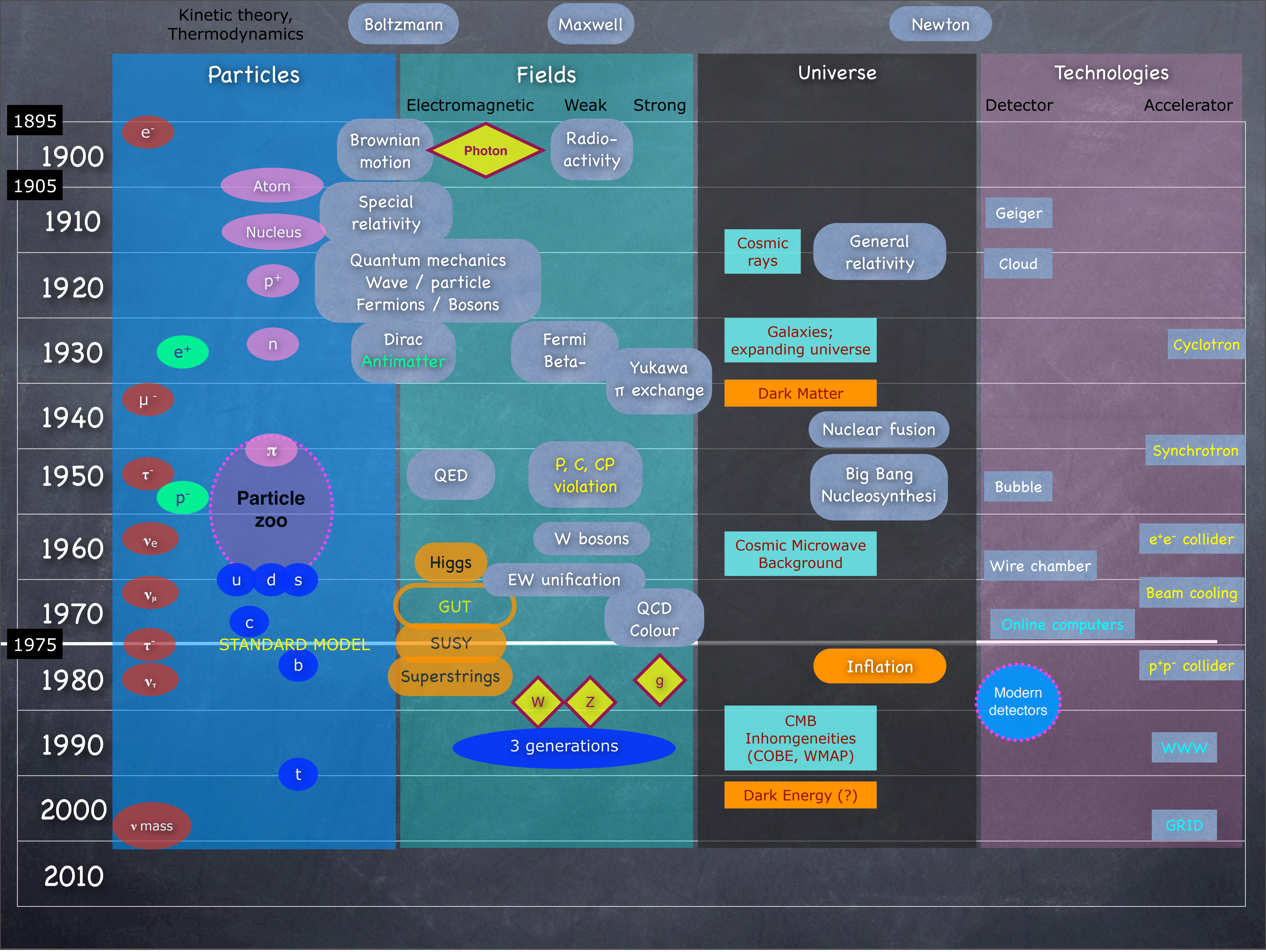

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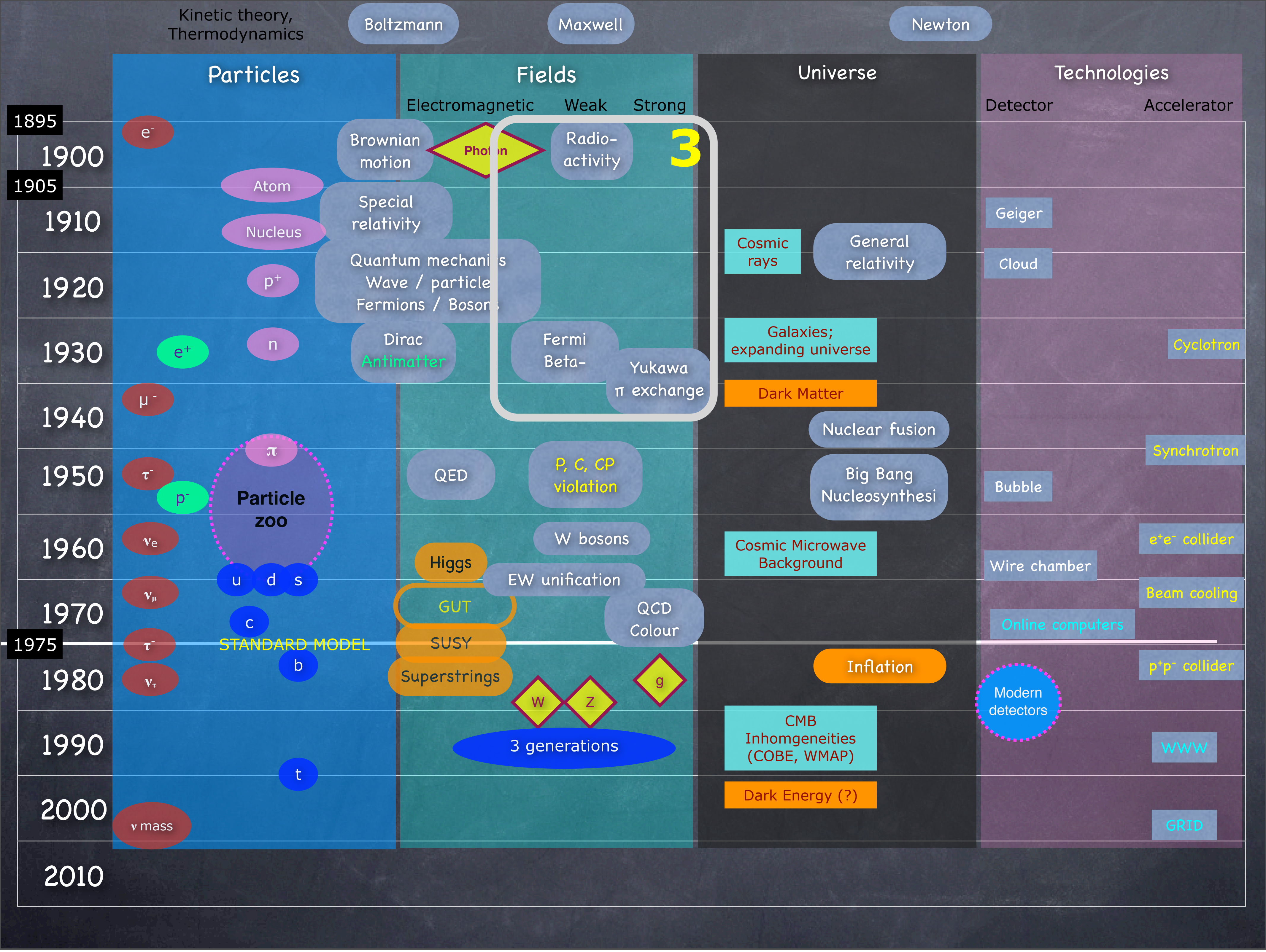

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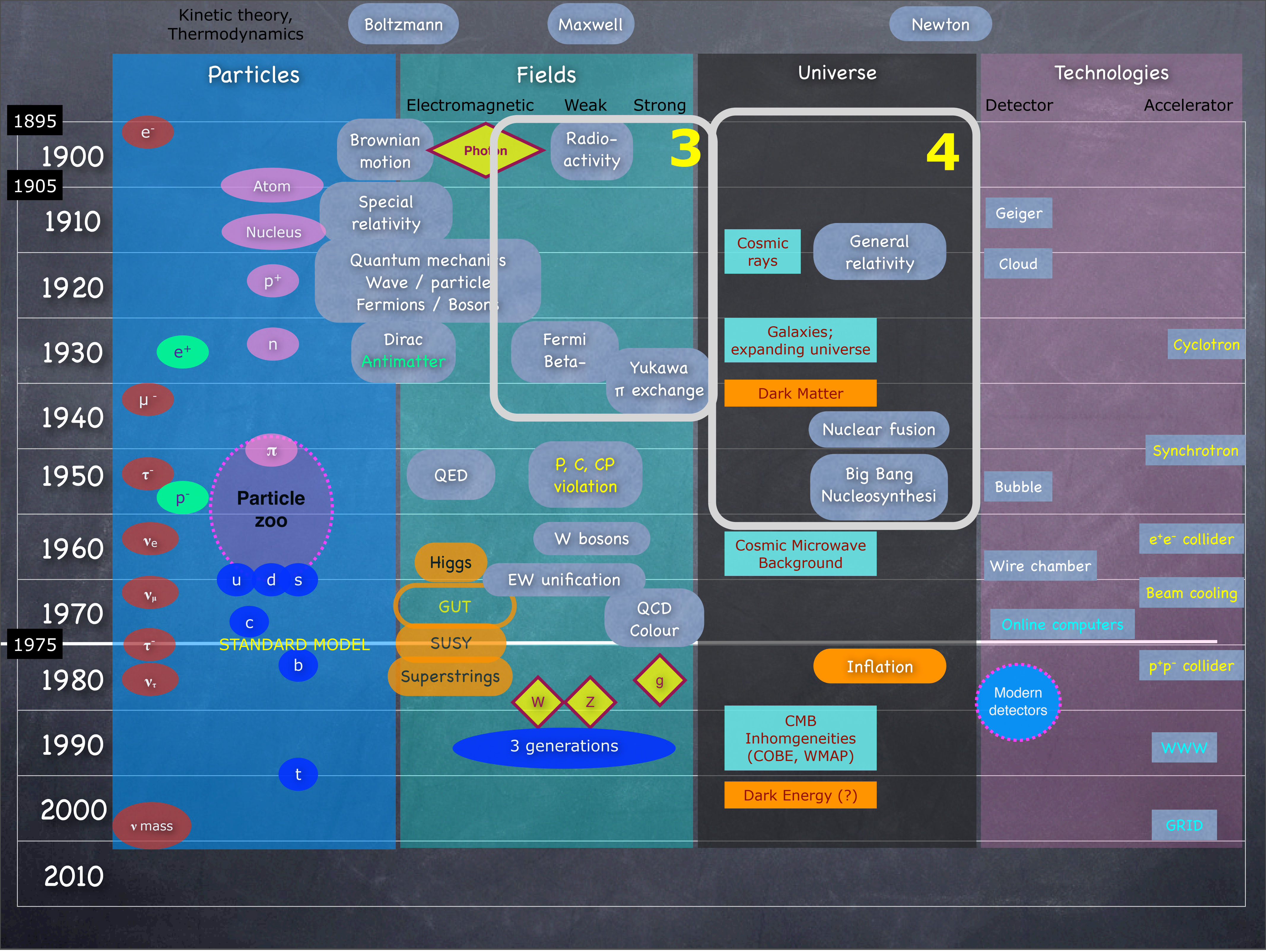
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Back to the beginning of the century - another interaction was being discovered

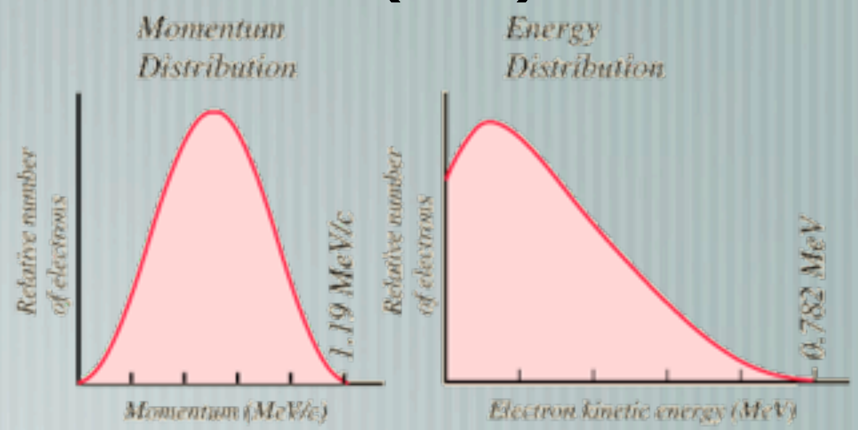
The "Weak Interaction" - Radioactivity

1896: Henri Becquerel discovered radiation from U crystals

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

1911: Continuous (?) energy spectrum of 'beta'-rays (electrons) - energy conservation?

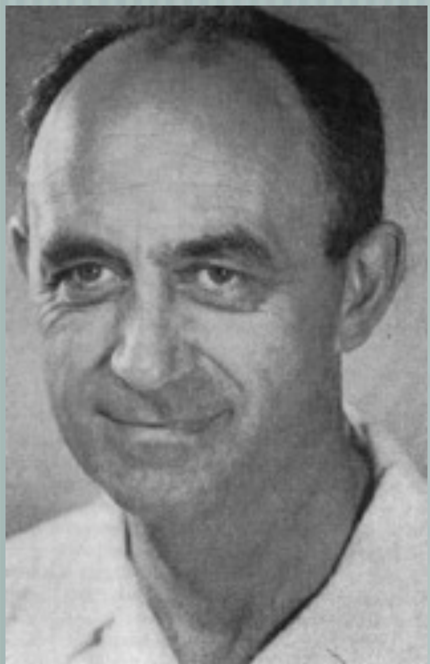
Z --> (Z+1) + e ?



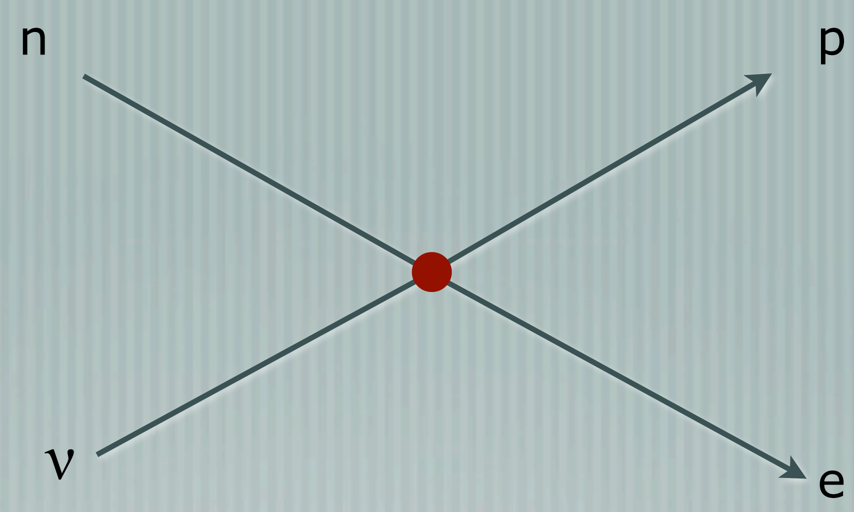
1930: Wolfgang Pauli postulates existence of 'neutrino': **n --> p + e + ν**

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

The "Strong Interaction" - Nuclear forces


Yukawa (1934)

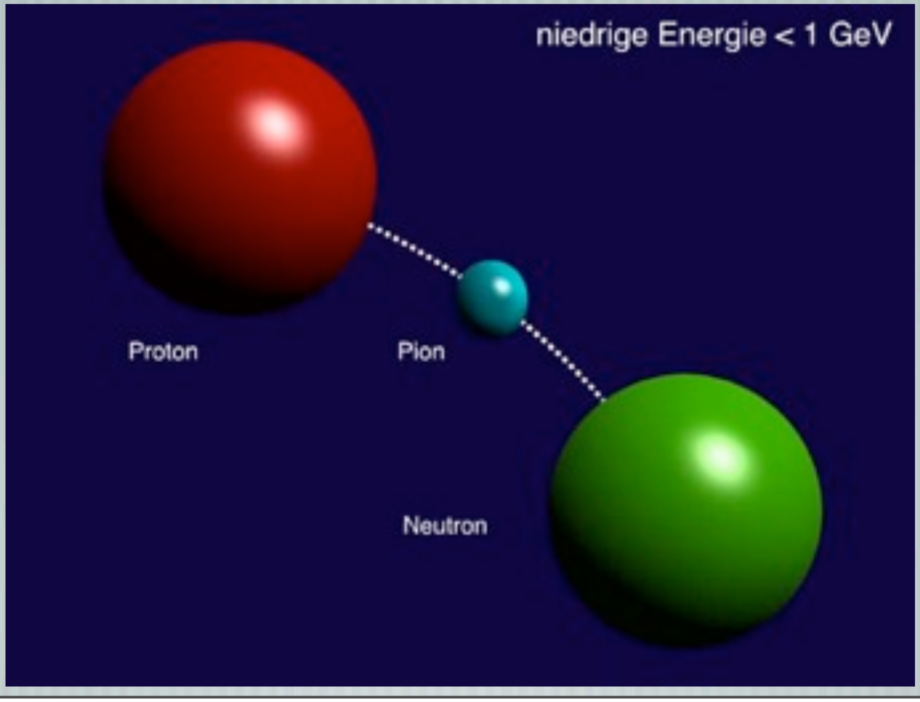
What keeps the protons and neutrons together in the nucleus?

1) This force must be stronger than the electromagnetic repulsion

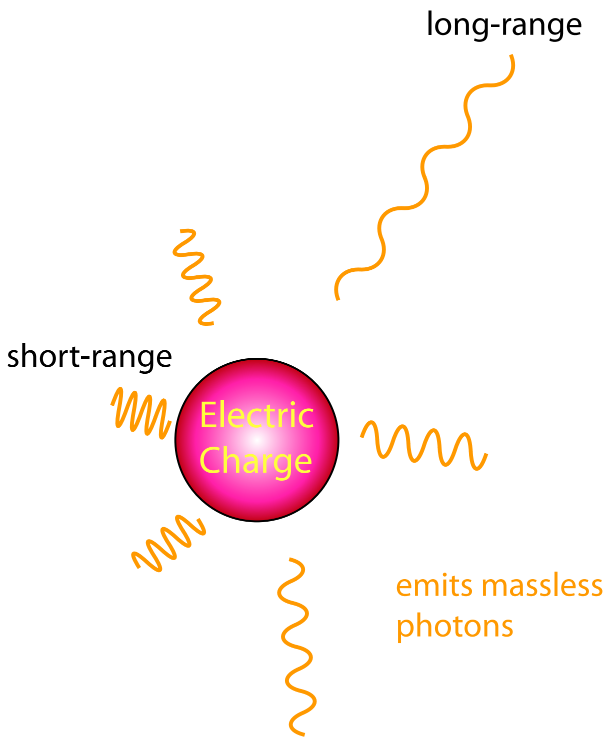
2) It must be of short range (~ 1-2 fm) to explain the size of nuclei

Yukawa's idea:

a massive particle ("pion") is exchanged between two nucleons



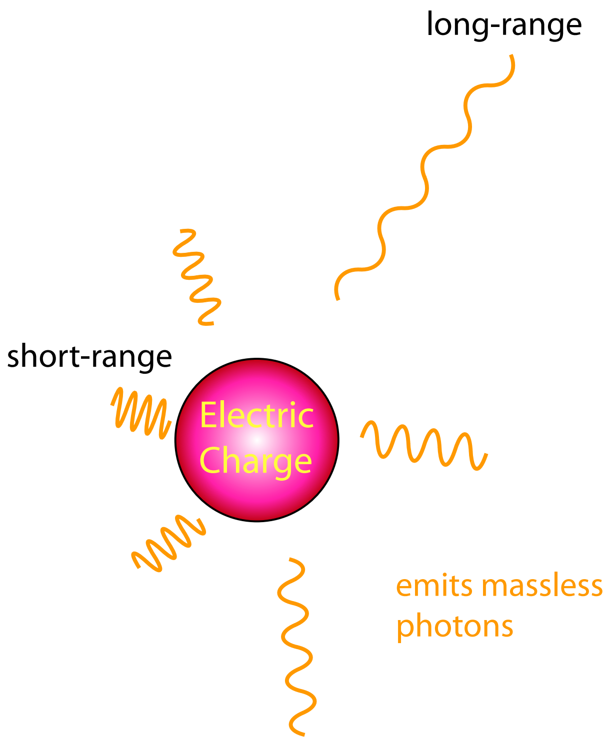
Electromagnetic

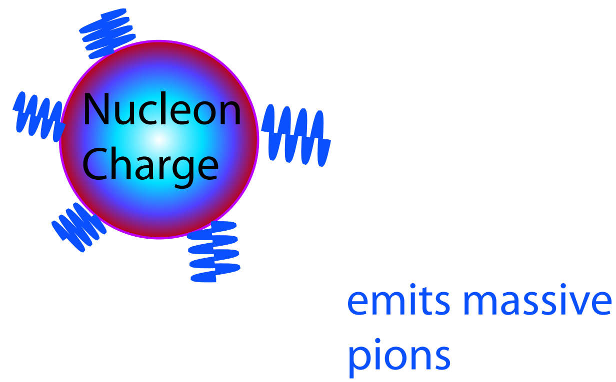


$$V(r) = -e^2 \frac{1}{r}$$

Coulomb law

Electromagnetic vs Nuclear





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

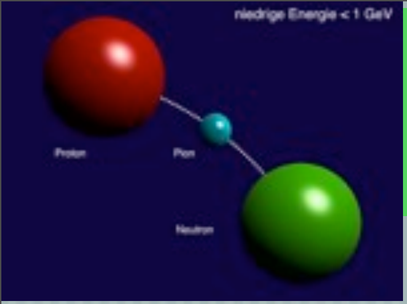
$$r = c\, \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

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

Coulomb law

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

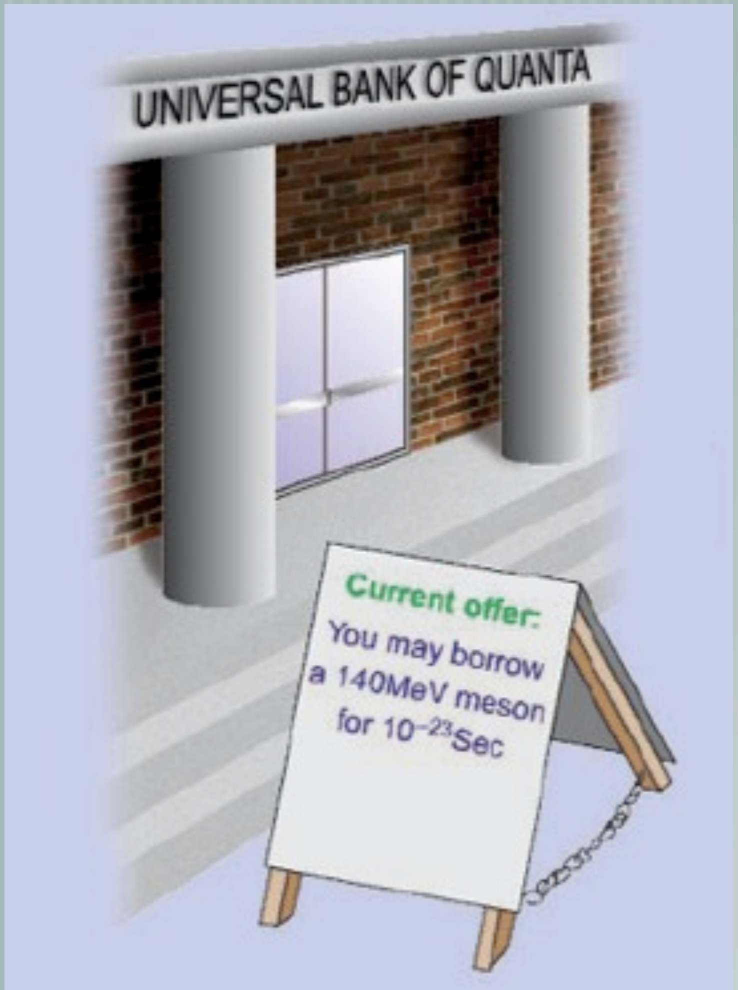
Yukawa potential ~ Modified "Coulomb" law



Fields

'Strong' interaction

Metaphors for 'particle exchange'



G. Gamov

Allowed by uncertainty relation: 1.4 fm ~ 140 MeV

4

The Universe

4

The Universe

Before the 20th century, the Universe was a quiet place. Not much seem to happen.

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The Universe

Before the 20th century, the Universe was a quiet place. Not much seem to happen.

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"

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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.

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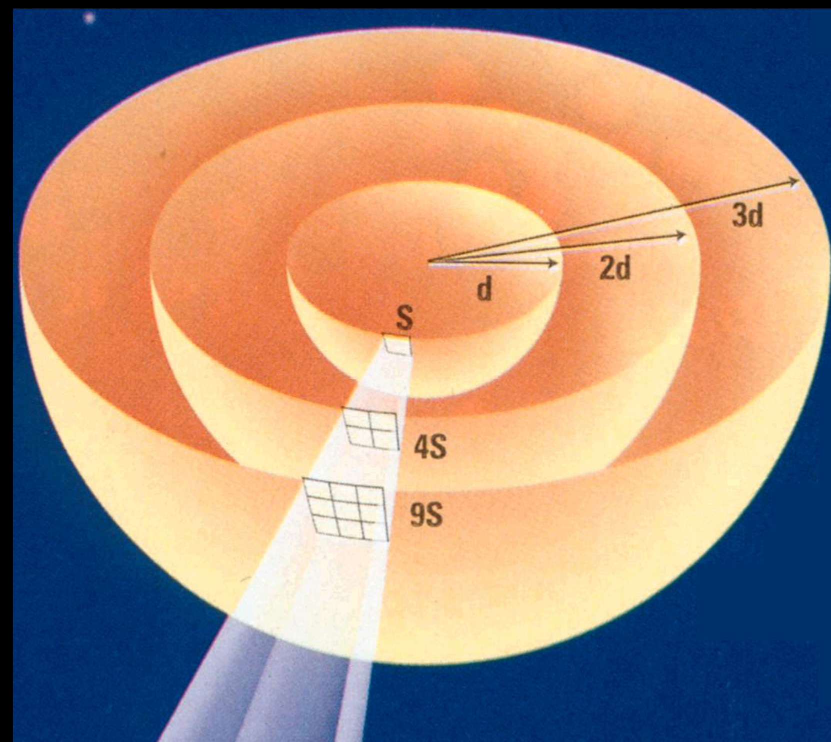


Formally:

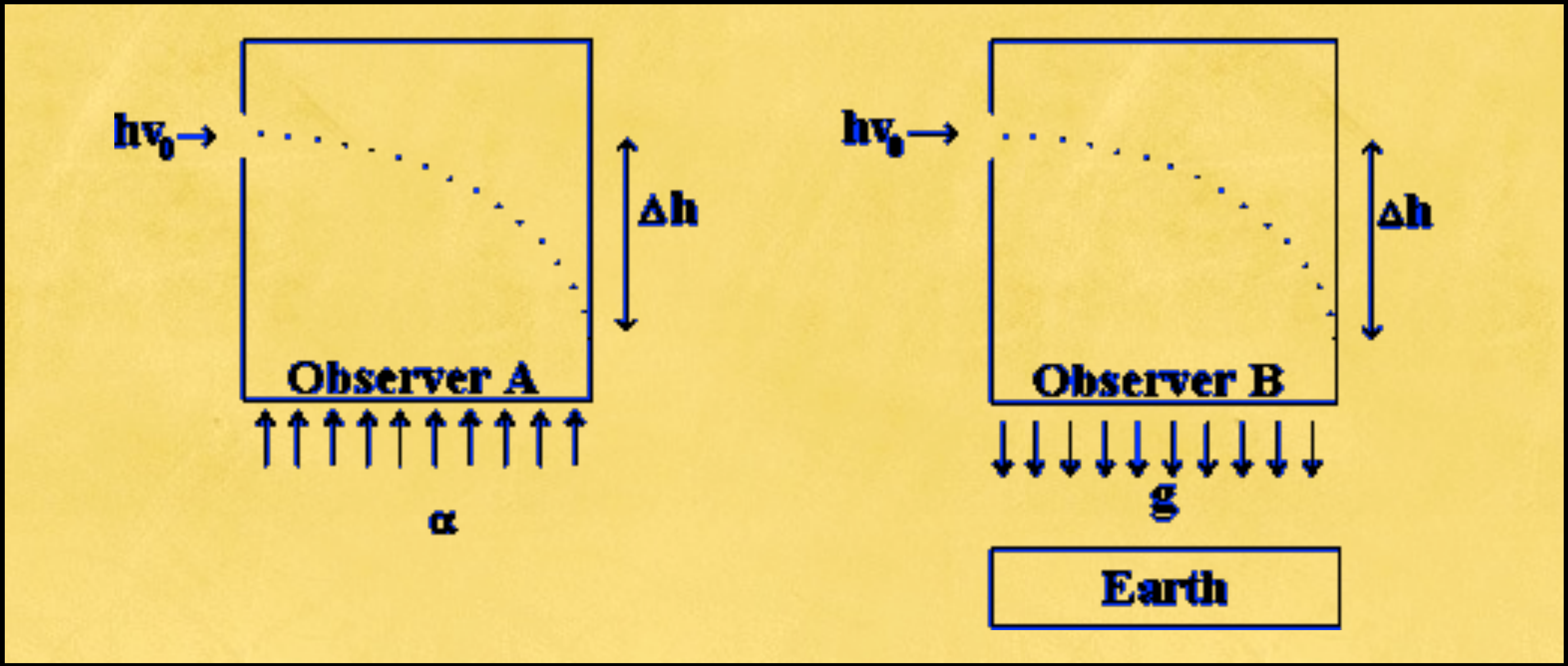
Each shell contributes ~ r^2
The light decreases with ~$1/r^2$
Light contribution from each shell = constant

Consequence:

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

1907

Equivalence Principle



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

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

Universe

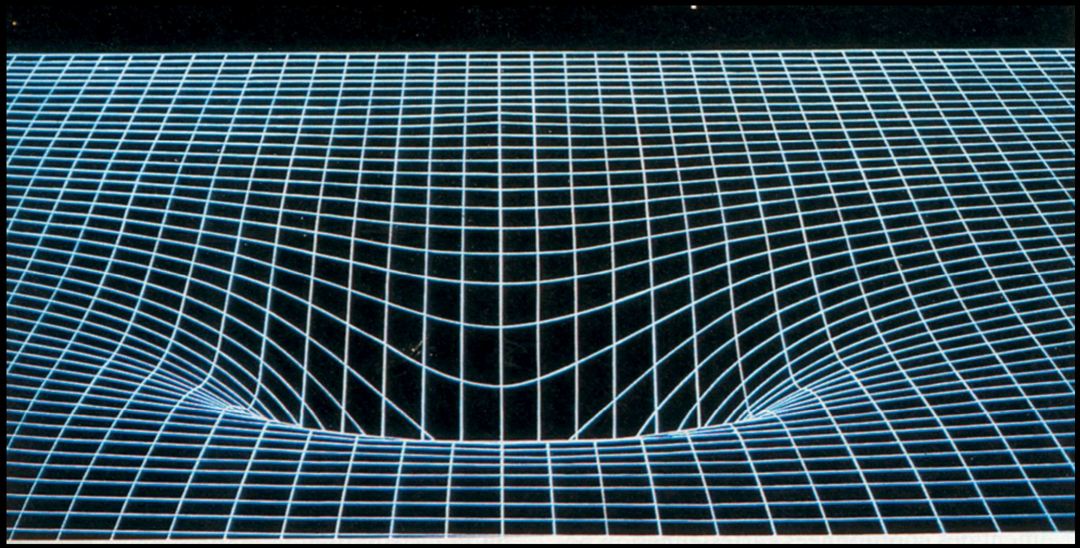
1915

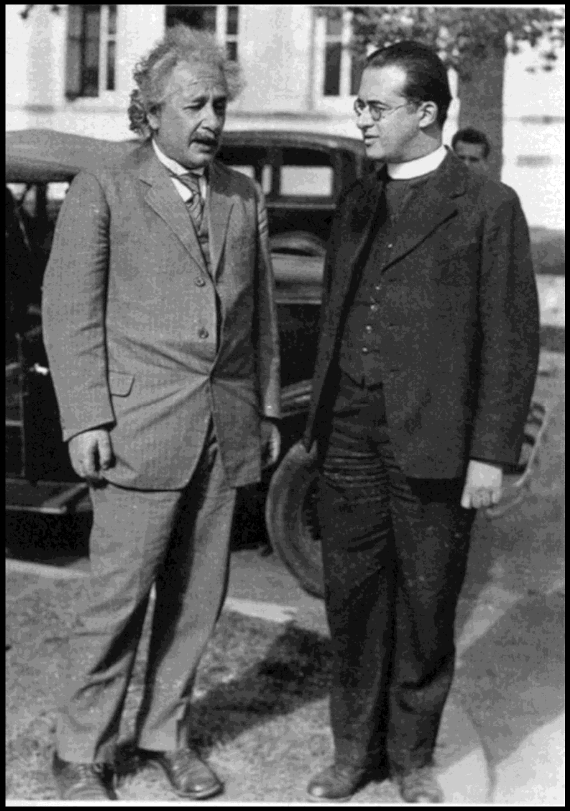
Light rays define the shortest path in space.
Accelerated elevator: light follows follows a parabolic path
Gravitational field: light path must be bent !
Space and time must be curved

Albert Einstein (1912-15) : General Relativity

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

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$





George Lemaitre (1927)

The whole Universe expands

Universe

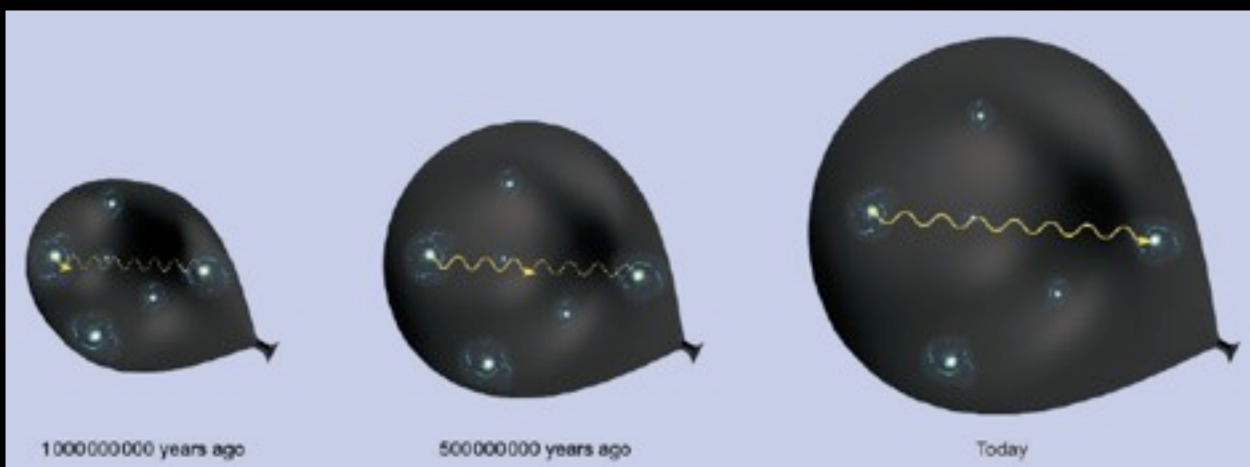
1915

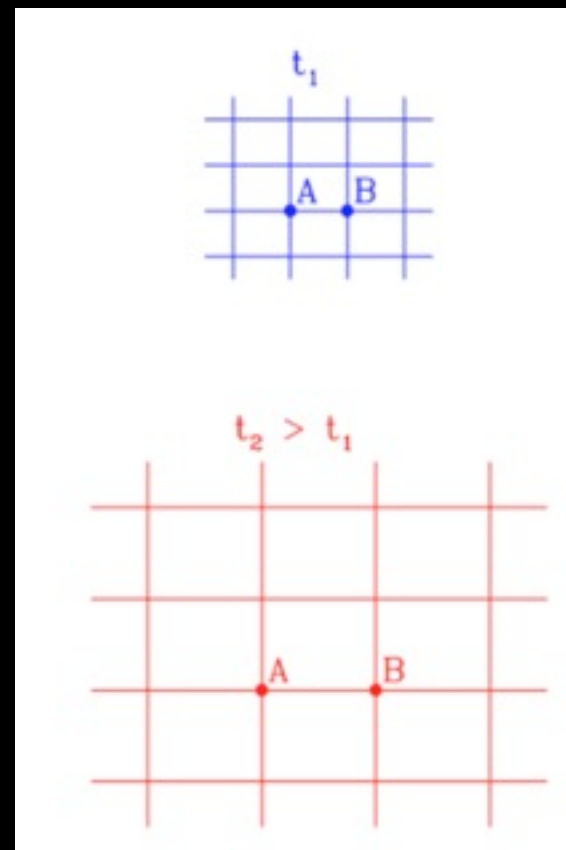
Friedmann described the expansion of the Universe using a scale factor a(t)

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

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

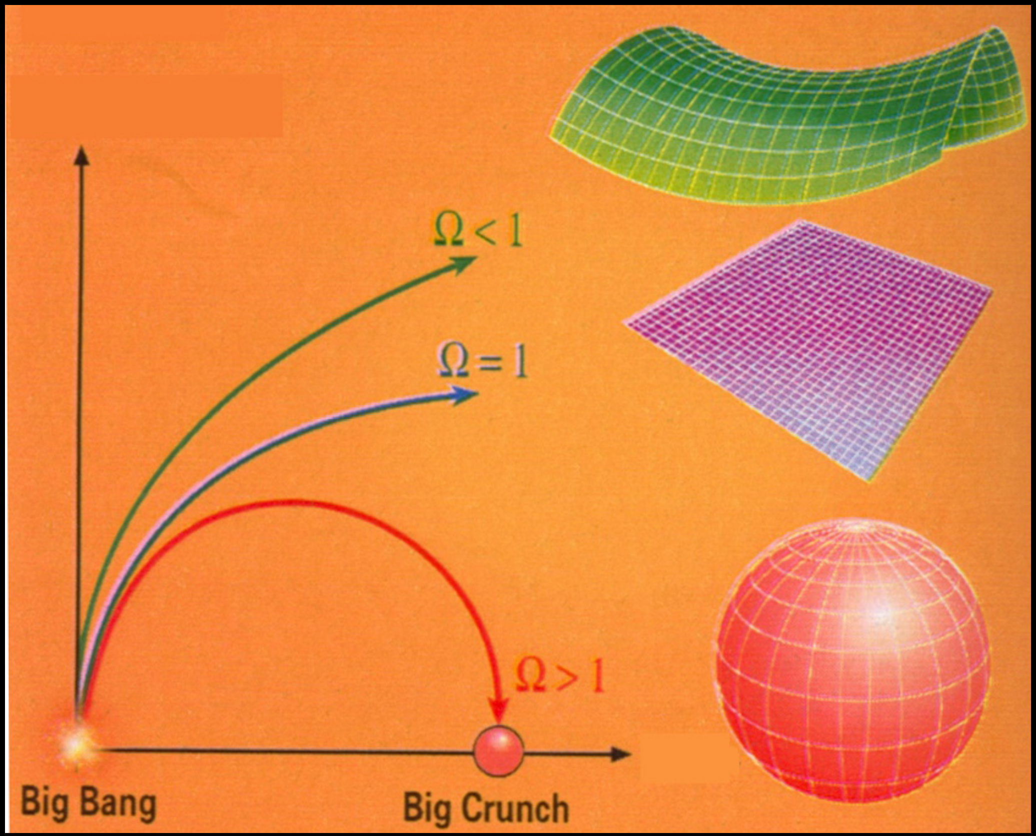
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{K}{a^2}$$





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.

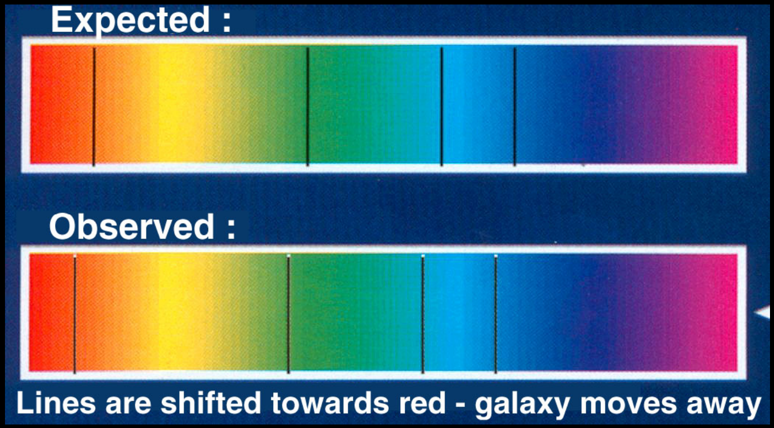
Therefore he decided to tinker with them, by adding a term named

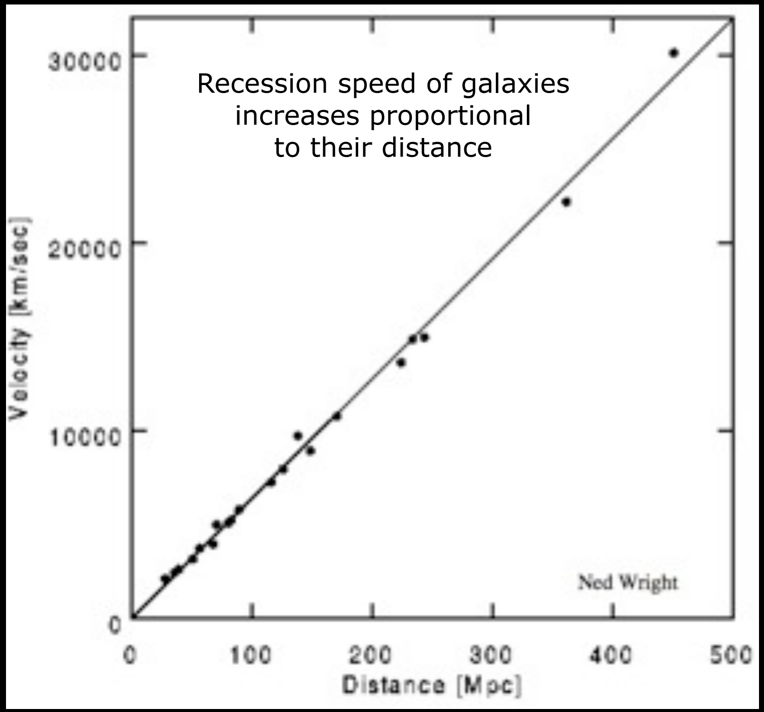
'cosmological constant'

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

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

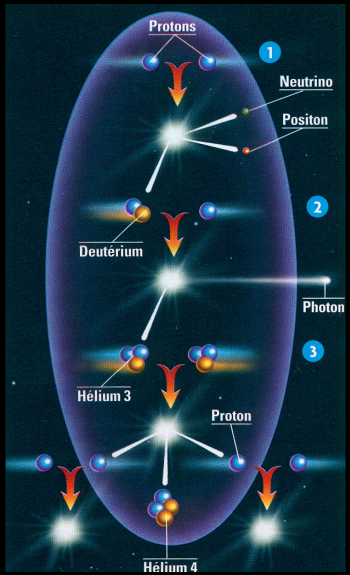
George Gamov

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)

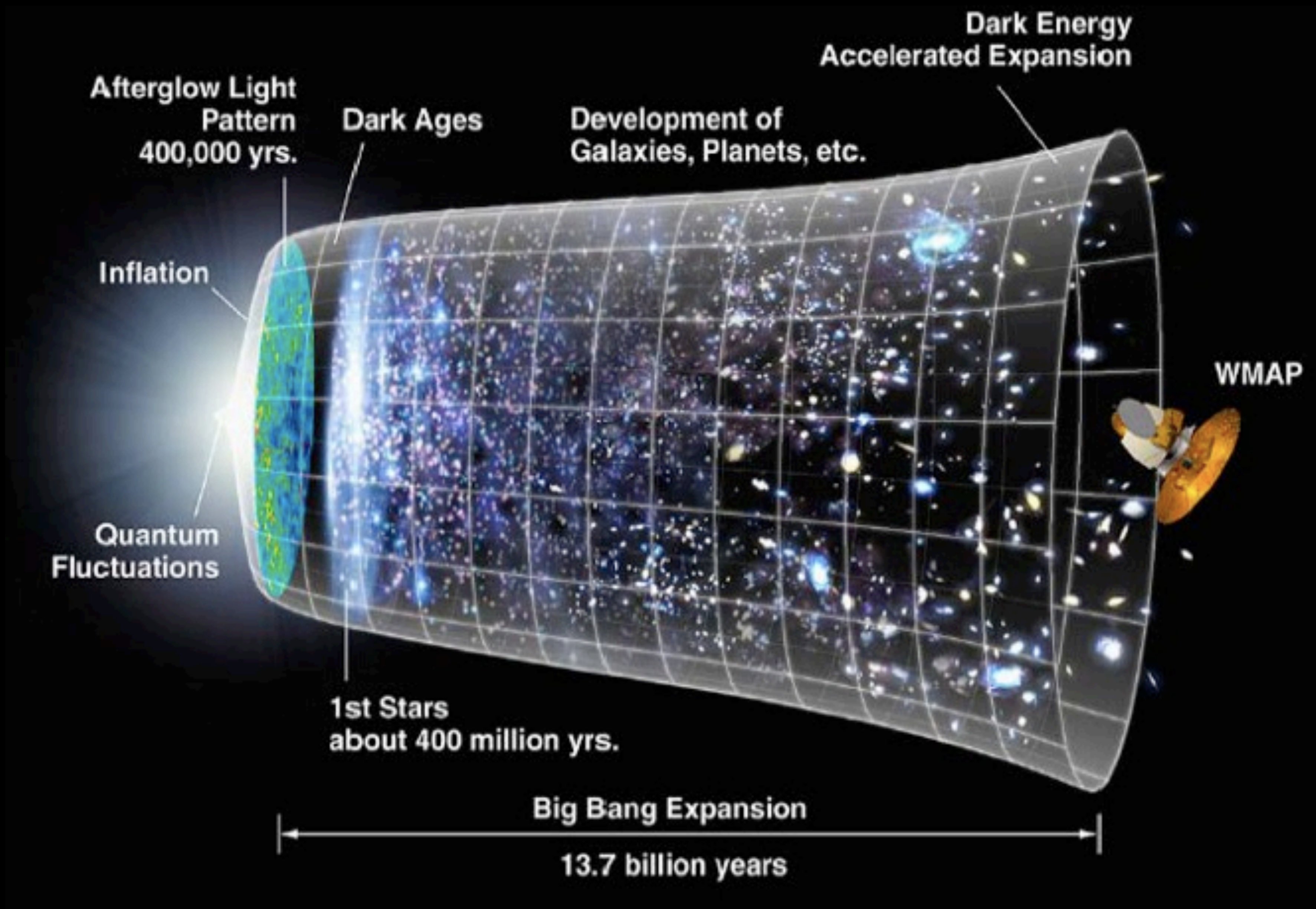


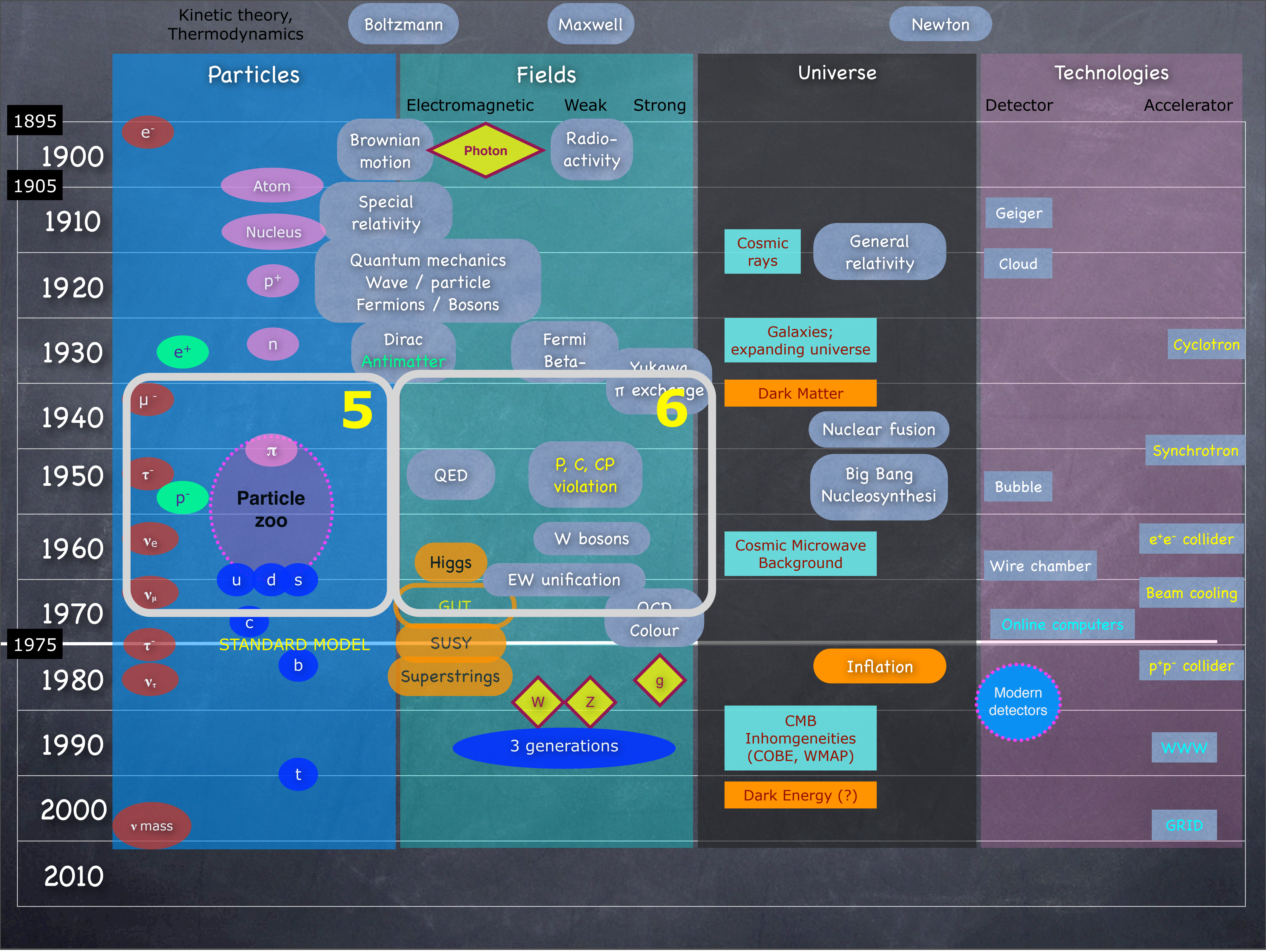
- In the first few minutes, there was just enough time to create the lightest elements
- There should be an 'echo' in form of a uniform black-body radiation (T ~ 5 K)

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

Today: Big Bang happened 13.7 ± 0.2 billion years ago

precise mathematical model - relates size, temperature to time

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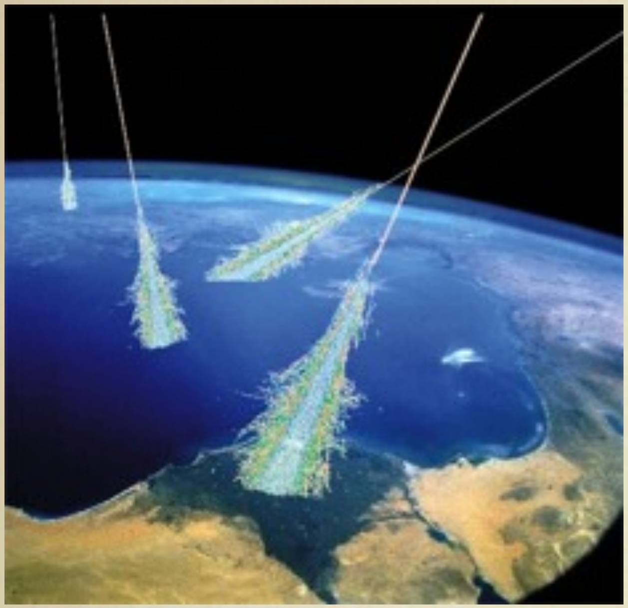
PARTICLE SPECTRUM

μ ⁻

1937



1913: Cosmic Rays were discovered

Physicists went on mountain tops for experiments!

1937: New particle discovered: negative charge, ~ 200 m_e

Very longe range in matter !? Not Yukawa's "pion" !

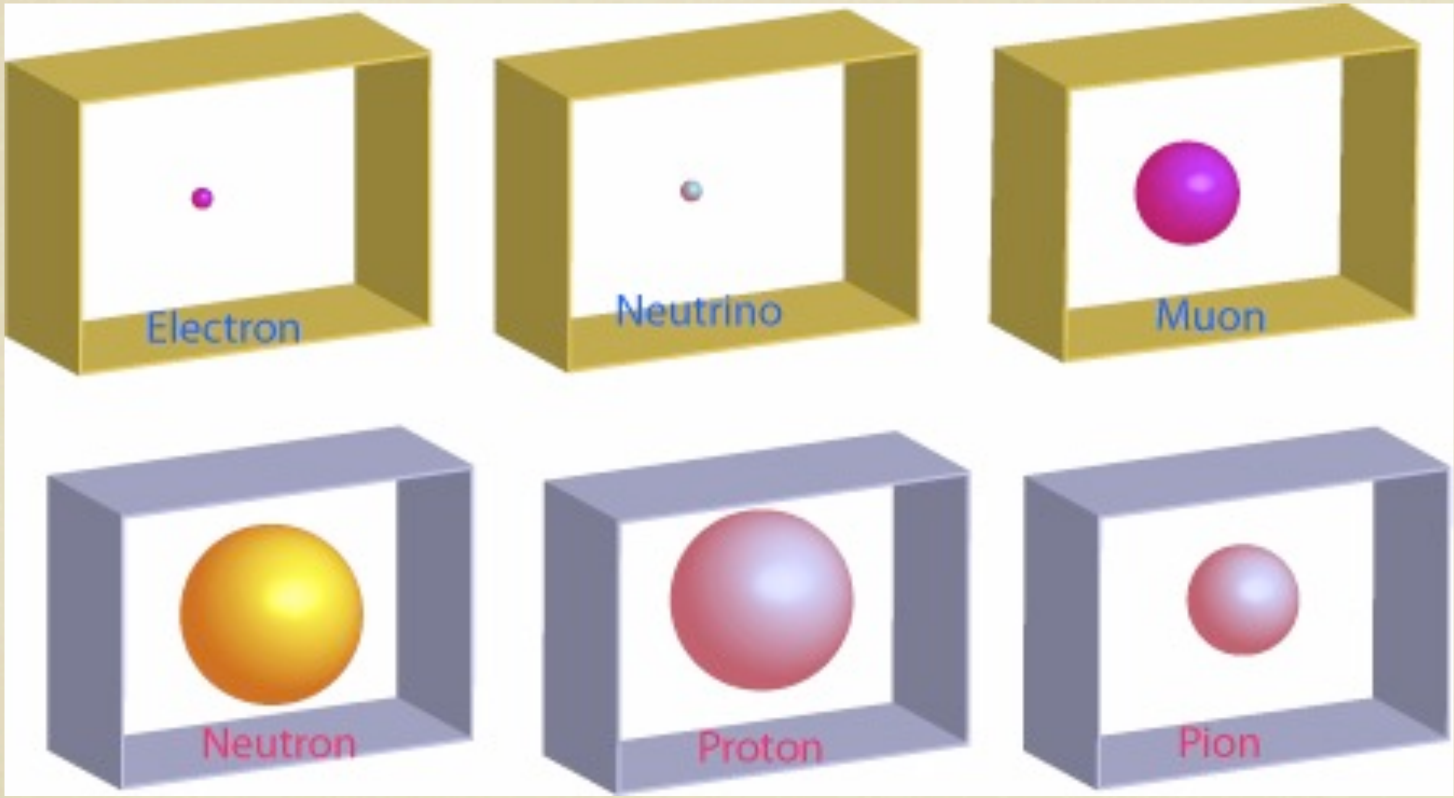
Muon = 'heavy electron'

I. Rabi: "Who ordered that ?"

1948: The "pion" was finally discovered (emulsions)

PARTICLE SPECTRUM

In 1948, the particle spectrum started to look ugly:



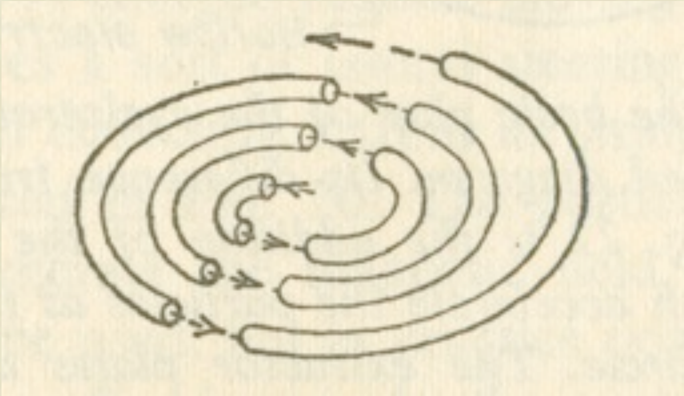
PARTICLE SPECTRUM

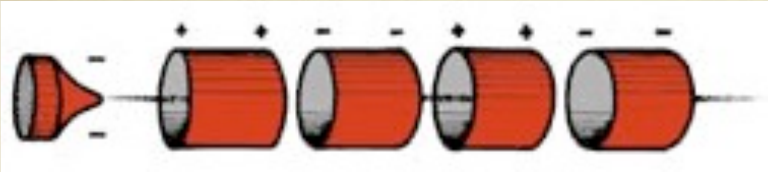
Accelerators

"Man-made cosmic rays"

Rolf Wideroe, 1928

Ernest Lawrence, 1931





Cyclotron

Use magnetic field to bend particles into circular orbit
Particles pass through same accelerating gap many times and reach higher energies

1931: 80 keV
1932: 1000 keV
1939: 19 MeV*
1946: 195 MeV ("synchrocyclotron")

* first limitations by relativistic mass increase

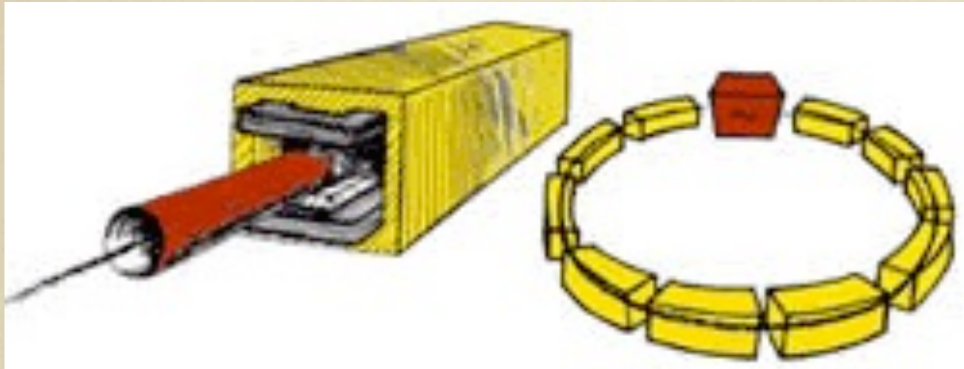
Linear accelerator

Accelerate particles between electrode gaps
Tune RF frequency to match particle motion

PARTICLE SPECTRUM

1931 - 1955

Accelerators (2)



Synchrotron

Similar to cyclotron, but change magnetic
field to keep particles on the same orbit
(also overcomes relativistic mass increase)

1947: US constructs two 'synchrotrons'

Brookhaven (1952) - 3 GeV

Berkeley (1954) - 6.2 GeV ('antiproton')

1954: Europe competes with US

CERN (1959) - 24 GeV

Brookhaven (1960) - 30 GeV

Detectors

Geiger counters
Cloud chambers
Emulsions
Bubble chambers

Cerenkov counters
Photomultipliers
Spark chambers

After 1967:

Wire chambers
Drift chambers
Calorimeters

PARTICLE SPECTRUM

Particle zoo

1950- 1968

**With new accelerators and detectors,
the "particle zoo" grew to more than ~ 200 'elementary particles'**

Mesons

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

Pions

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

Kaons

η'

Eta-Prime

η

Eta

ϕ

Phi

$\rho^+ \ \rho^- \ \rho^o$

Rho

Baryons

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

Delta

Λ^0

Lambda (strange!)

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

Sigma (strange!)

Ξ^0, Ξ^-

Sigma(very strange!)

What was the underlying structure ?

PARTICLE SPECTRUM

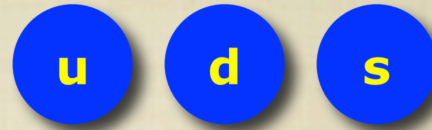
1963

SU(3) - Classification scheme based on 'quarks'

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

1) 3 types of "quarks" : up, down, strange



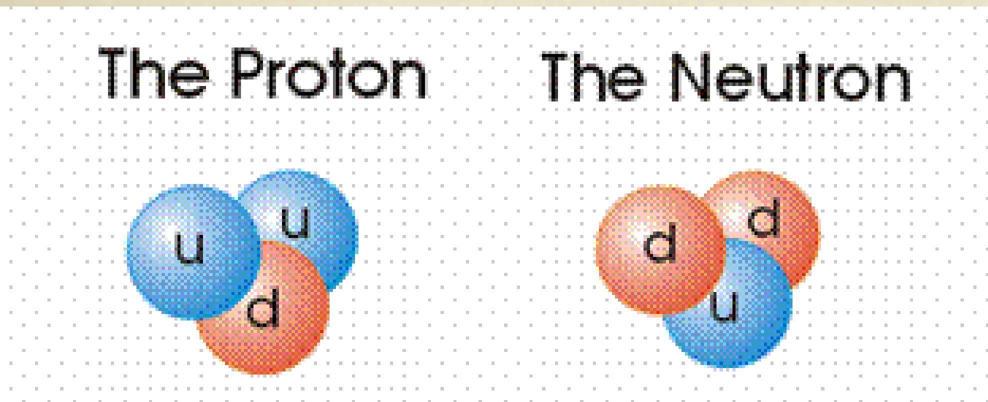
+2/3 e -1/3 e -1/3 e

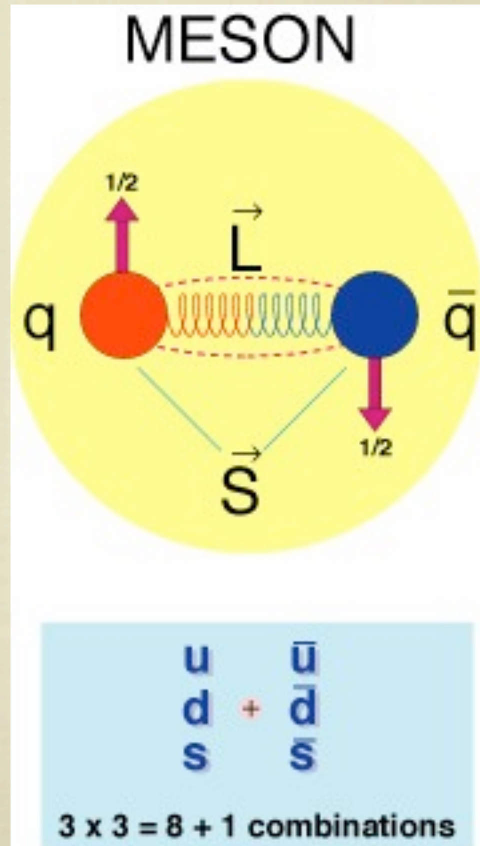
2) Carry electric charges: +2/3, -1/3, -1/3

3) Appear in combinations:

Meson = quark+antiquark

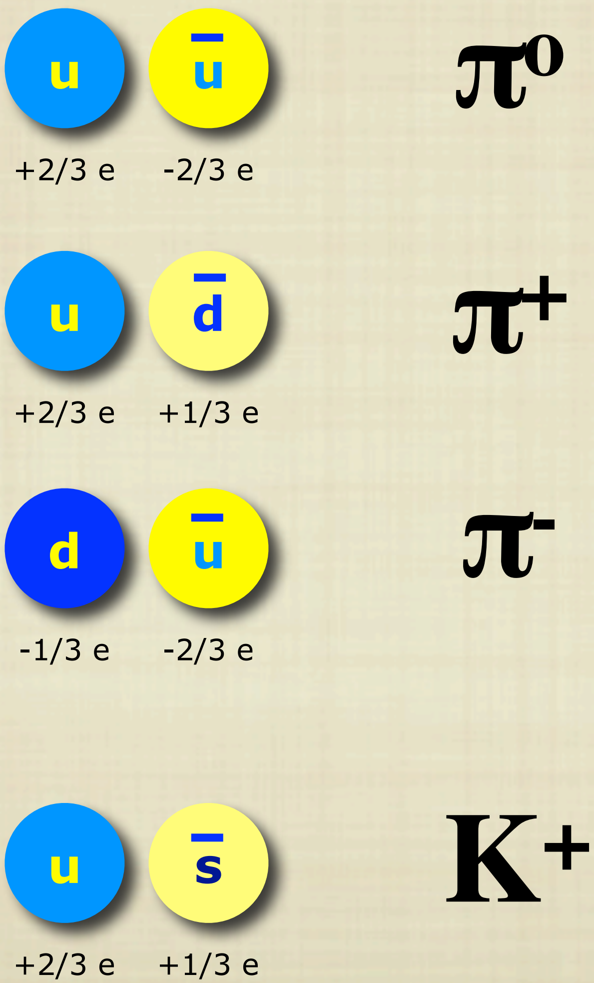
Baryon = quark(1) + quark(2) + quark(3)

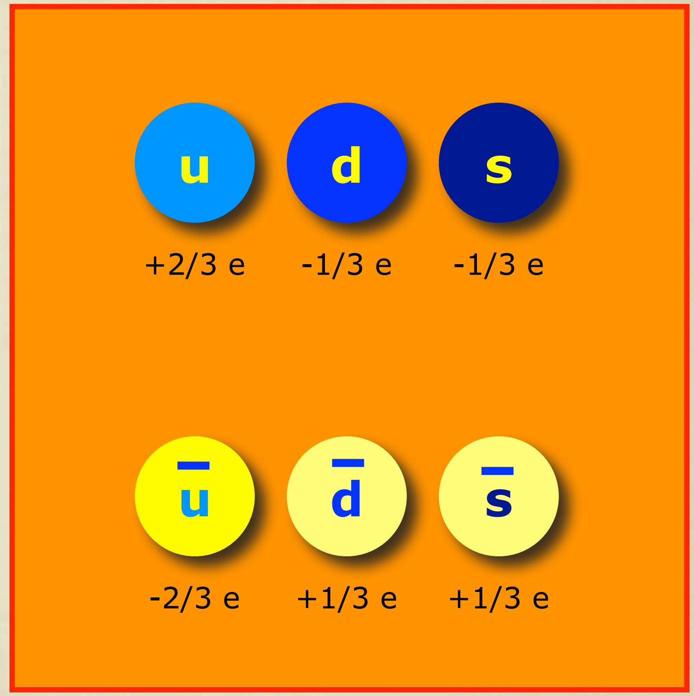




PARTICLE SPECTRUM

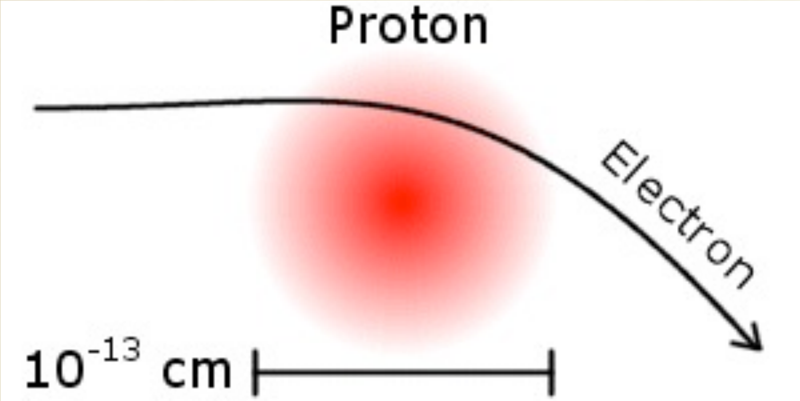
Some mesons (quark+antiquark):





Discovery of quarks

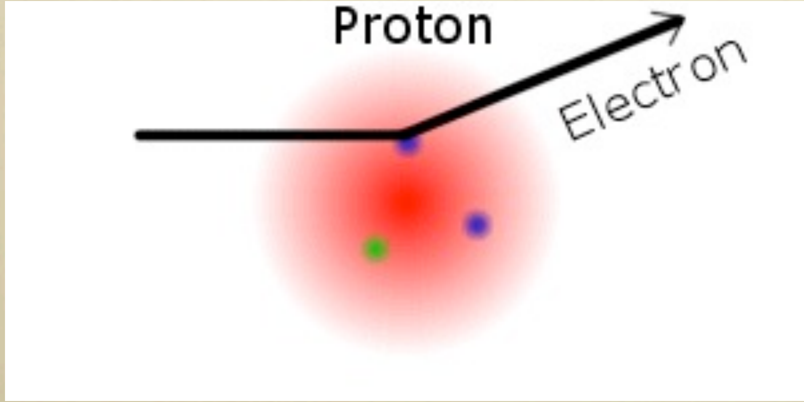
Electron-Proton scattering



1956 Hofstadter: measured finite proton radius

Stanford Linear Accelerator Centre

1967 Friedmann, Kendall, Taylor (SLAC):
'hard scattering' of electron on three 'point-like particles'

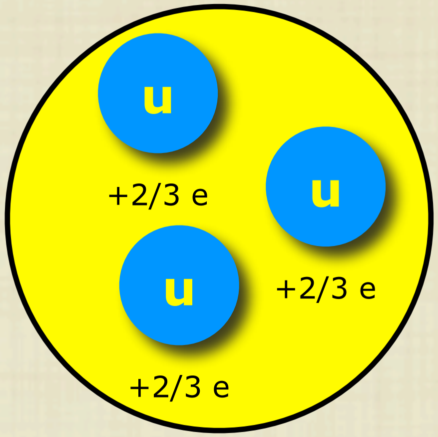


Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

The concept of "Colour" charge

PROBLEM: three fermions are not allowed to be in identical states (Pauli exclusion principle)

Δ^{++}



Since the three up-quarks must have parallel spin - there are in a symmetric state

The three quarks must be different in one quantum number: "colour"

(Bardeen, Fritzsch, Gell-Mann)

PARTICLE SPECTRUM

Quantum **C**hromo **D**ynamics

this has nothing to do with our visible colours, just an analogy

Theory constructed in analogy to QED

QCD: 3 different charges (“colour charge”) [red, green, blue]*

‘Strong force’ between quarks is transmitted by (8) gluons

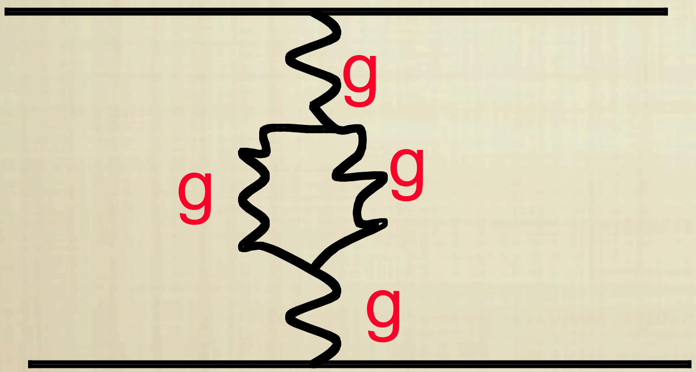
Dogma of QCD: Only colour-neutral bound states are allowed, explains:

MESONS = Quark-Antiquark
BARYONS = 3-Quark states

PARTICLE SPECTRUM

1973

GLUONS CARRY COLOUR CHARGE : SELF-INTERACTION !



At low energies, approximately:

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

For small distances, the force decreases:

asymptotic freedom