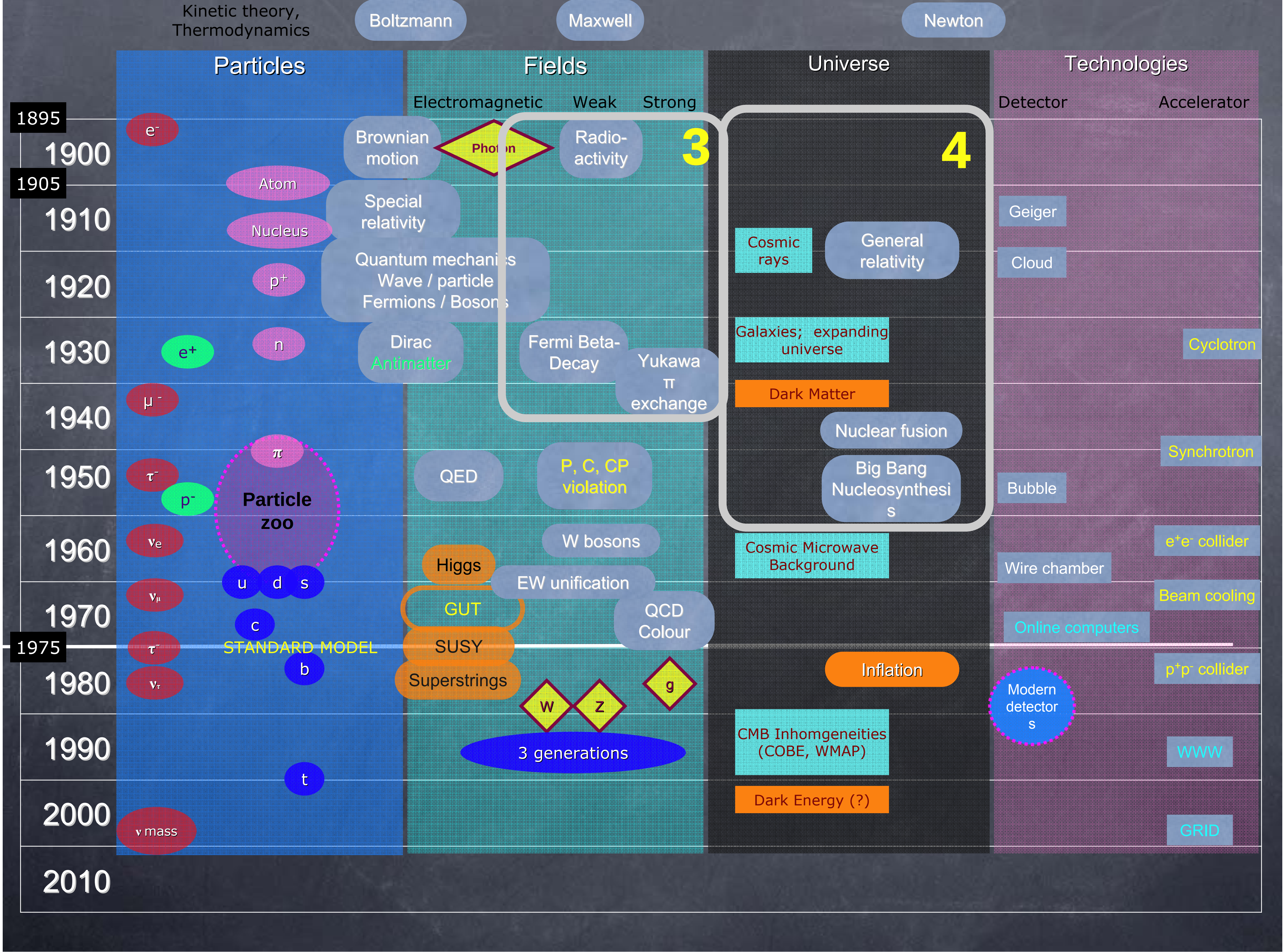

Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Universe
Technologies
Electromagnetic
Weak
Strong
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e-
Atom
Nucleus
p+
n
e+
μ -
π
Particle zoo
τ-
p-
νe
u
d
s
νμ
c
STANDARD MODEL
τ-
b
ντ
t
ν mass
Brownian motion
Photon
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Radio-activity
3
Fermi Beta-Decay
Yukawa
π
exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD
Colour
SUSY
Superstrings
g
W
Z
3 generations
4
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
e+e- collider
Wire chamber
Beam cooling
Online computers
p+p- collider
Modern detectors
WWW
GRID

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)

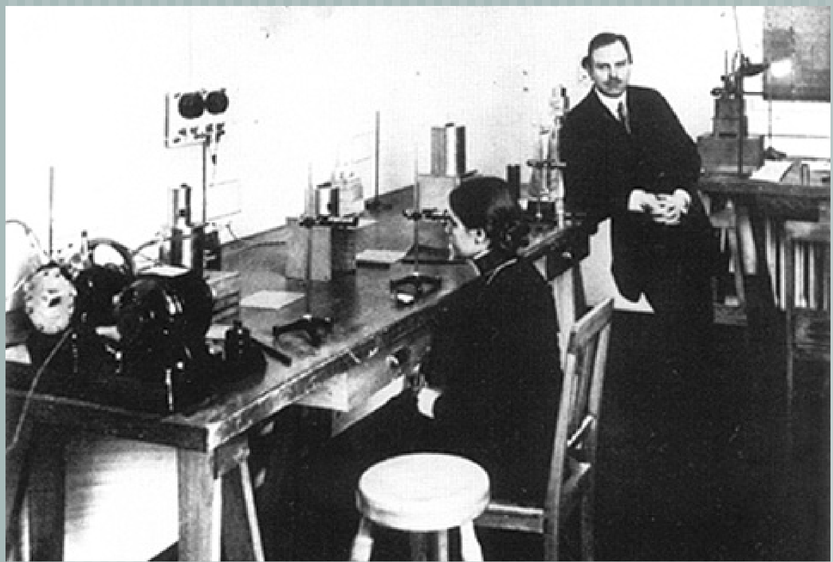
Radioactivity

Fields

'Weak' interaction

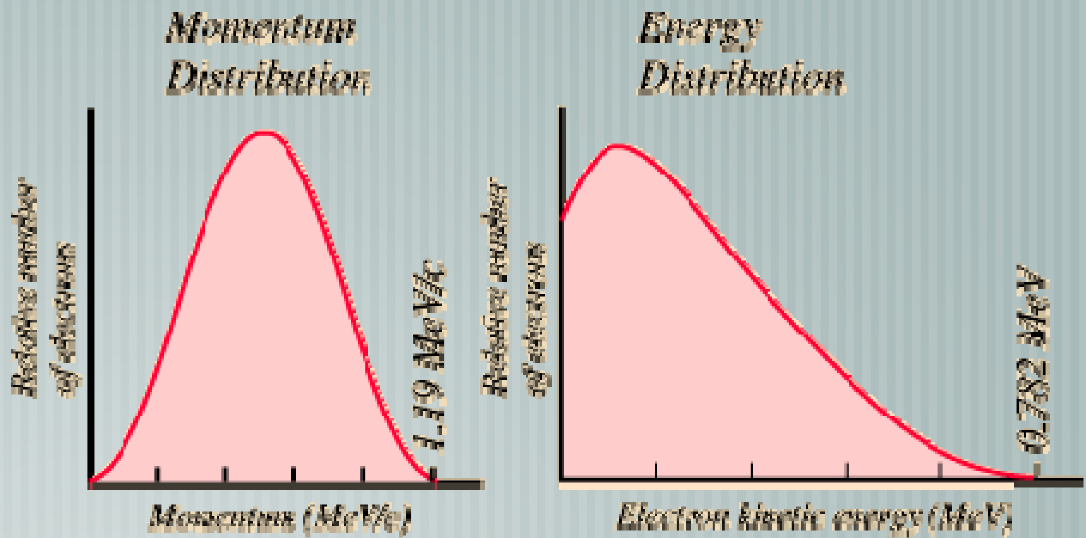
Beta decay of nuclei - electrons emitted with continuous energy spectrum !?

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



1911 Lise Meitner, Otto Hahn

Violation of energy conservation?



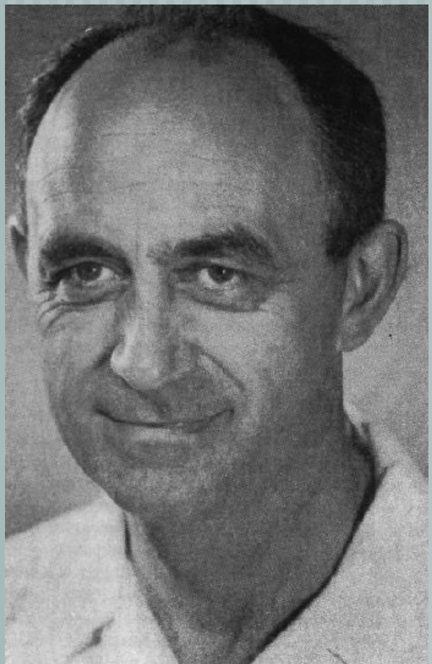
1930 Wolfgang Pauli: an **extremely light neutral particle*** is emitted in beta decay

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

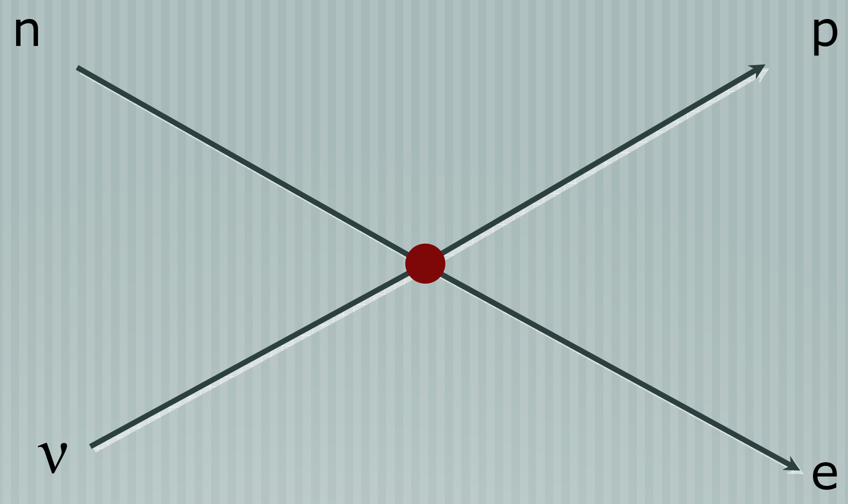
n --> p + e + ν

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

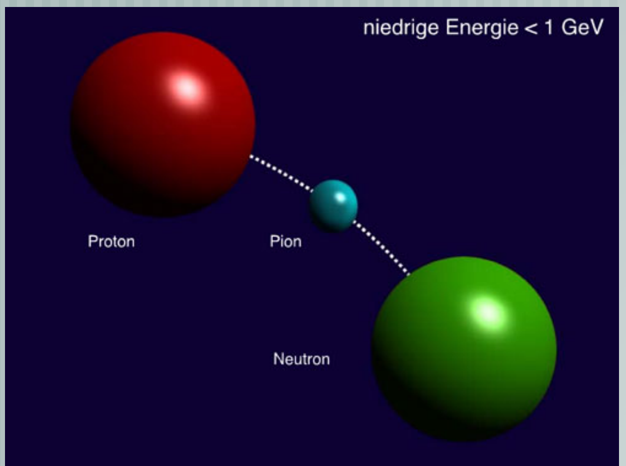
Back to the strong force: keeping protons and neutrons together

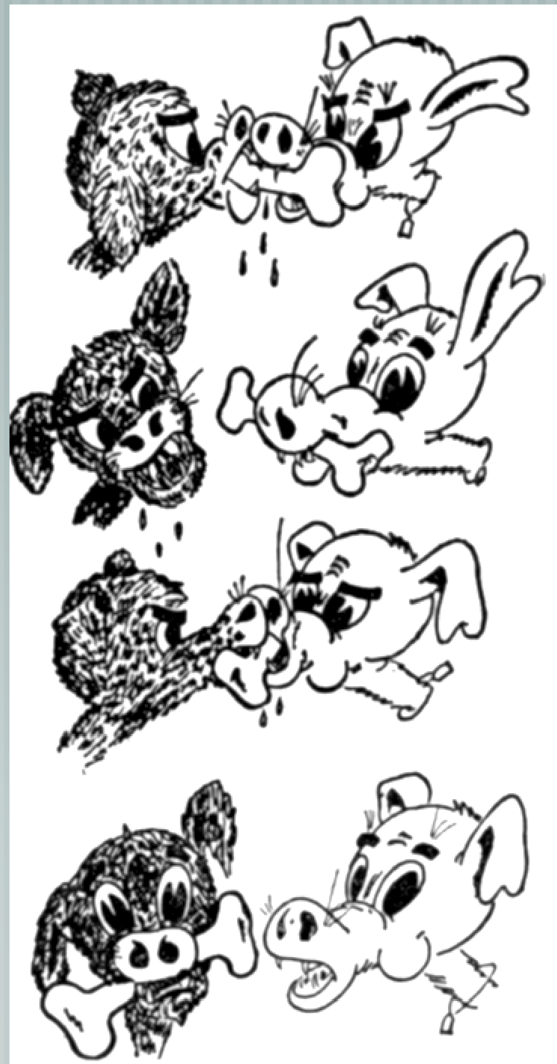
Yukawa (1934)

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

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

Olber's "Paradox"

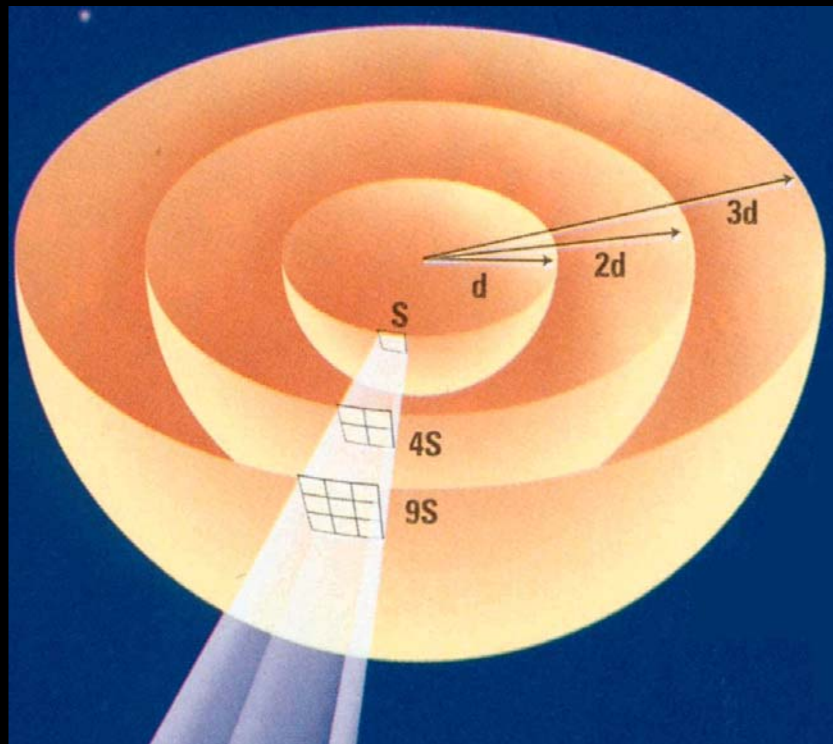
Heinrich Wilhelm Olbers (1823)

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.

Formally:

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

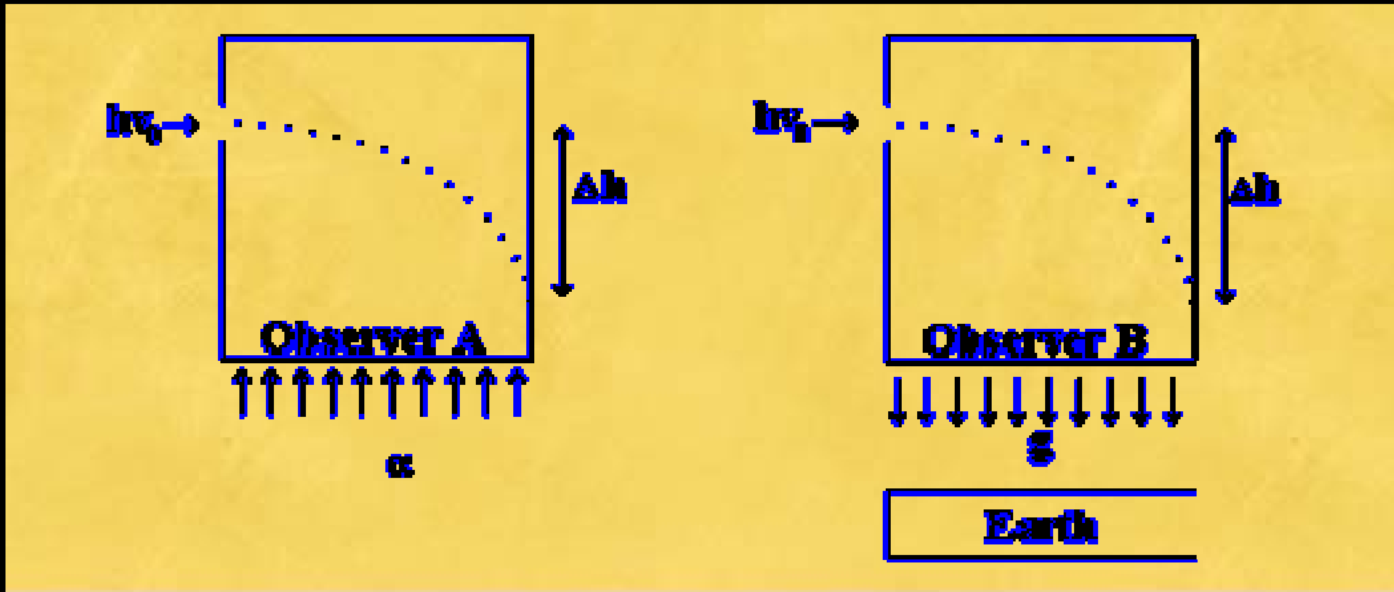
Consequence:
The Universe did not exist forever, or ...
The Universe has a finite size, or ...
Both



Universe

1907

Equivalence Principle



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

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

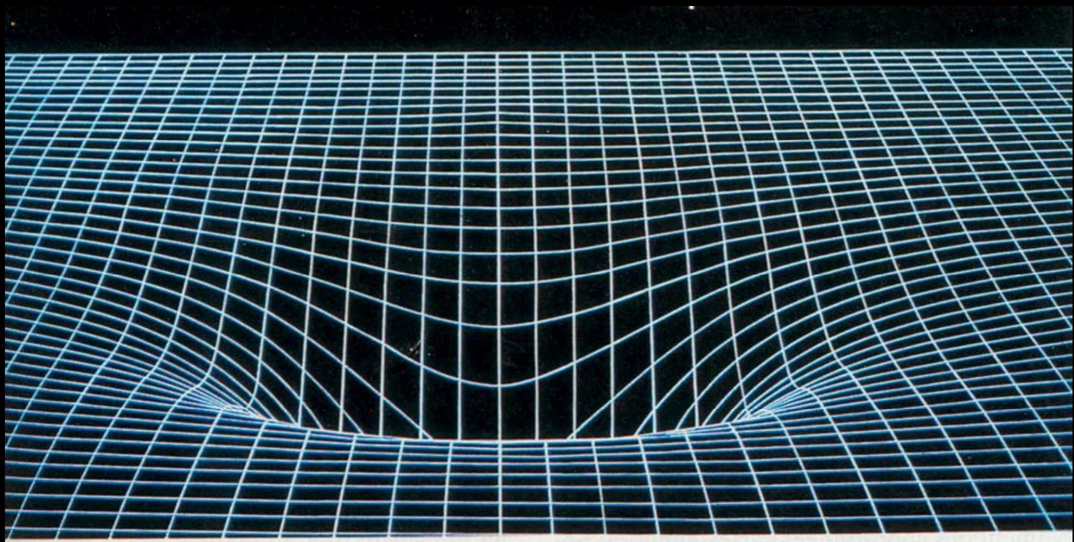
Universe

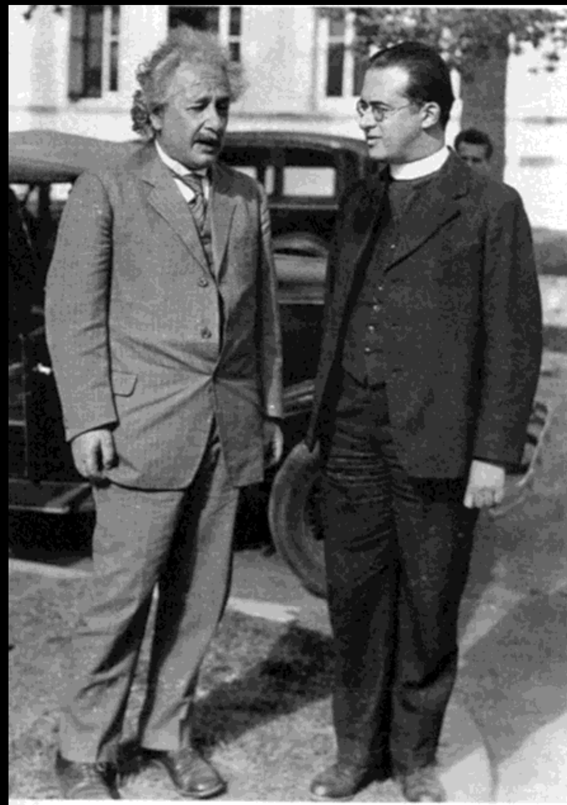
1915

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

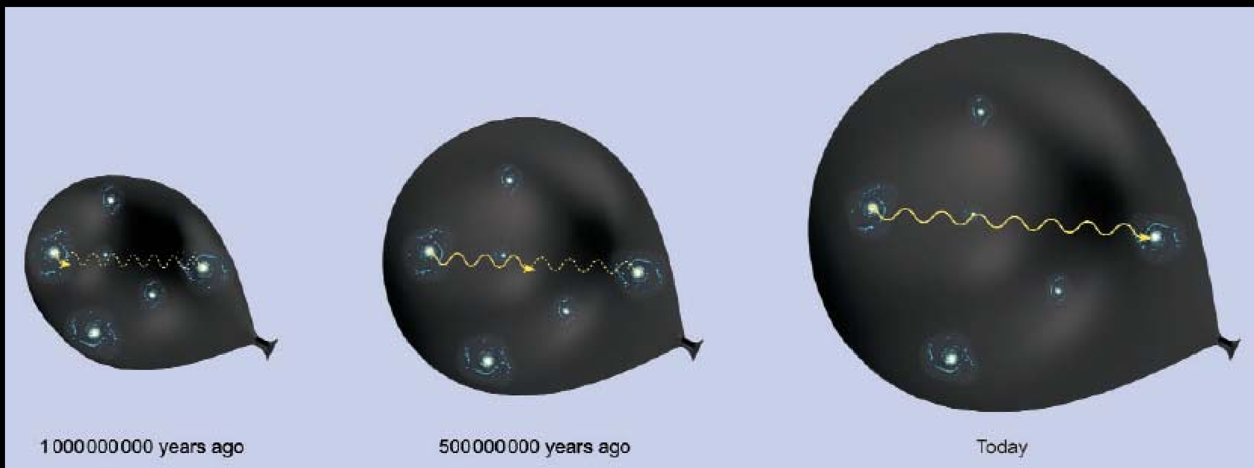
1915

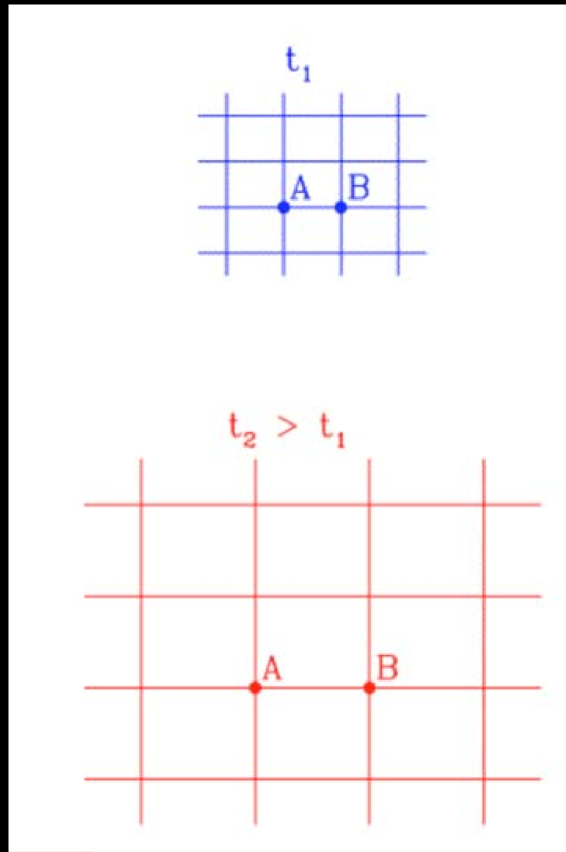
Friedmann described the expansion of the Universe using a scale factor a(t)

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

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

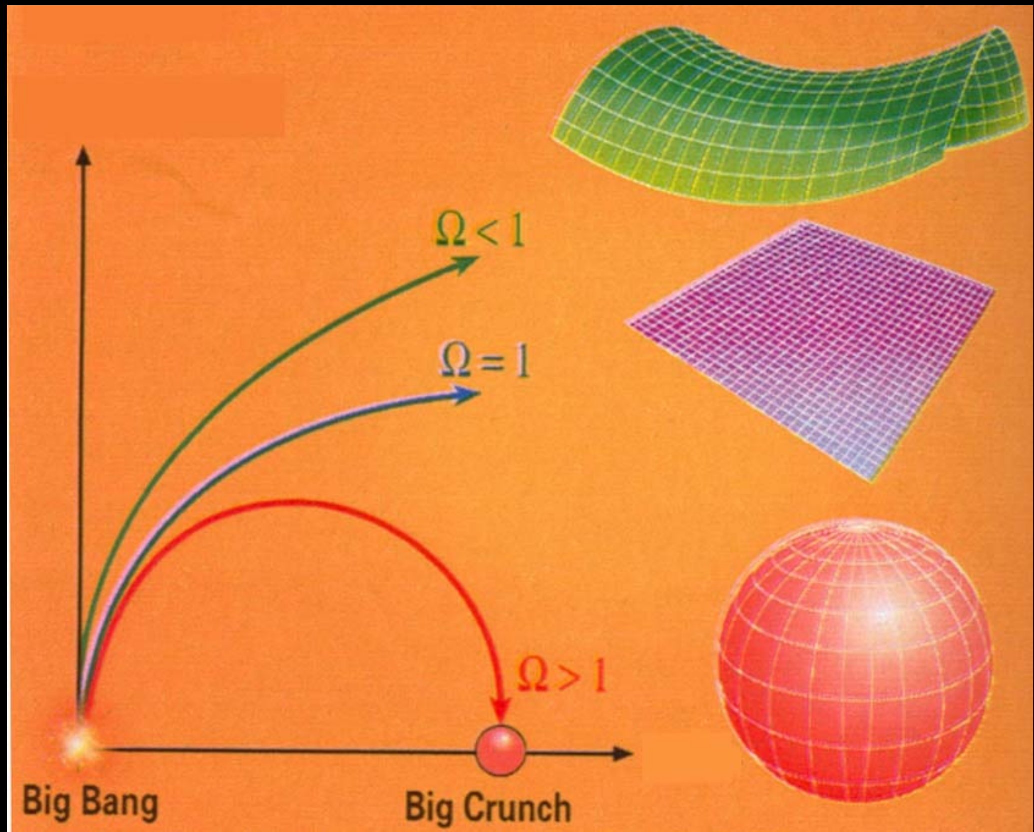
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{K}{a^2}$$





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

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.

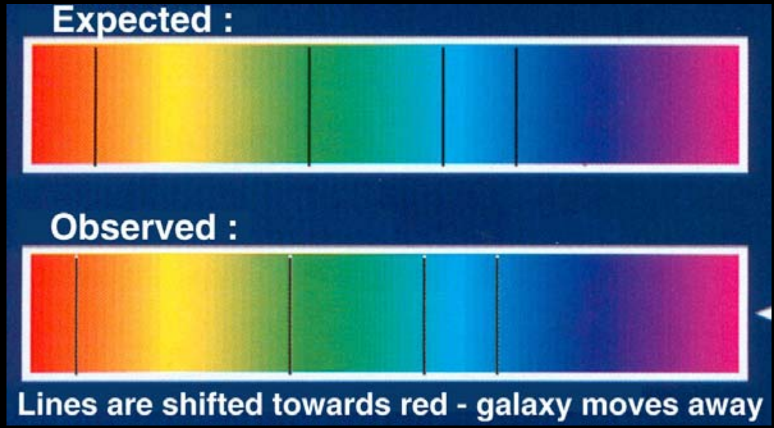
Therefore he decided to tinker with them, by adding a term named

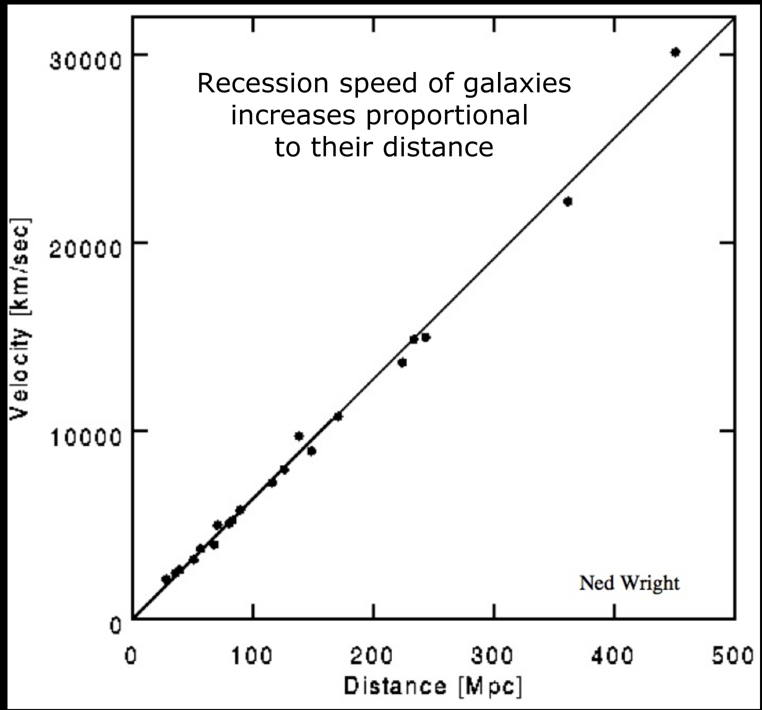
'cosmological constant'

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

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

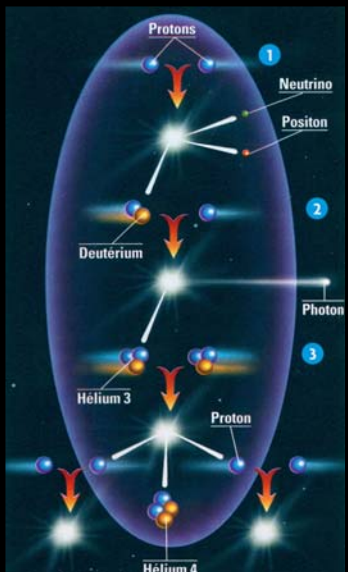
George Gamov

The Universe started from an extremely hot initial state

Then it expanded rapidly, while cooling down

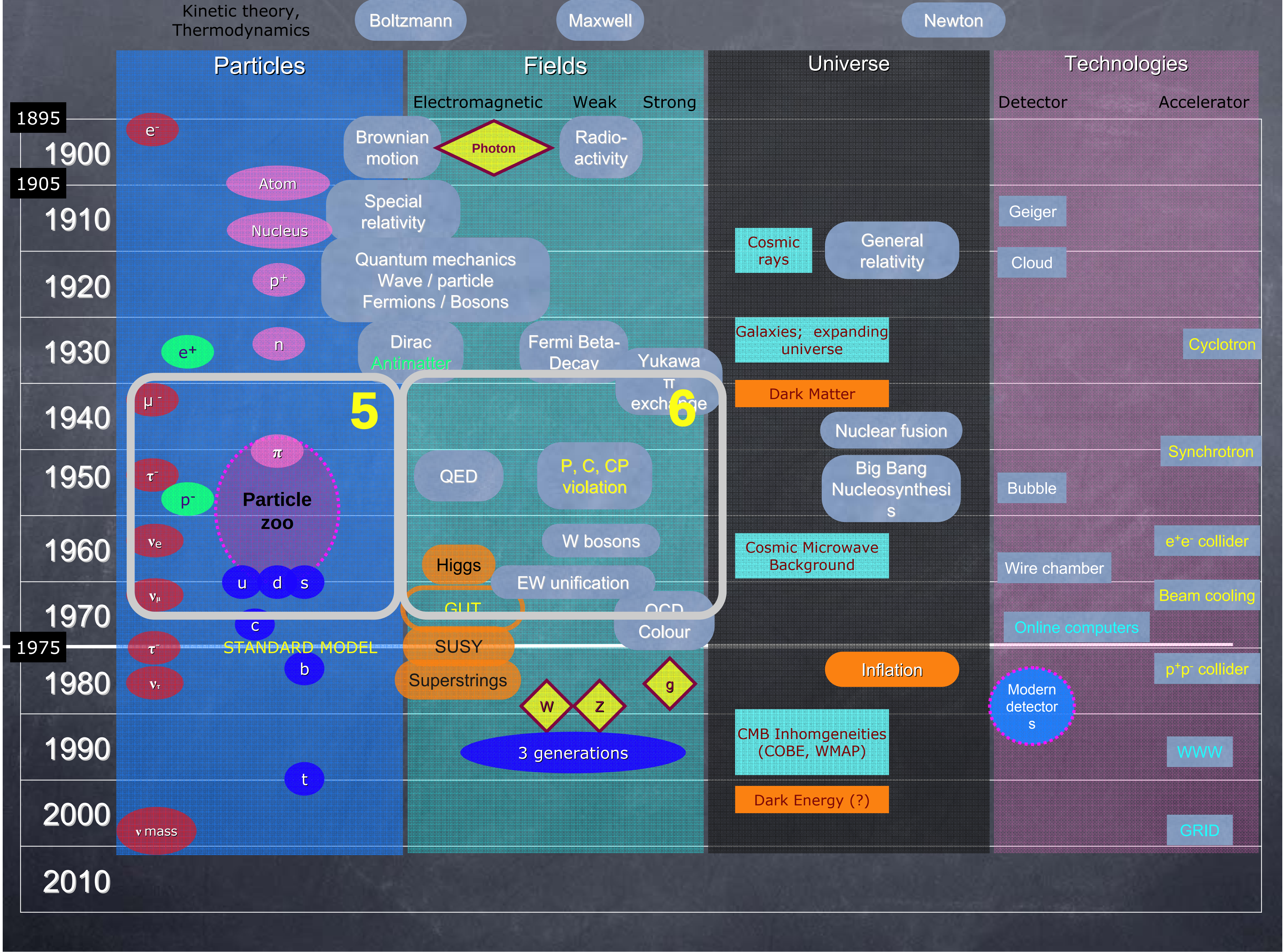
In very early times, the Universe was mostly radiation

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.

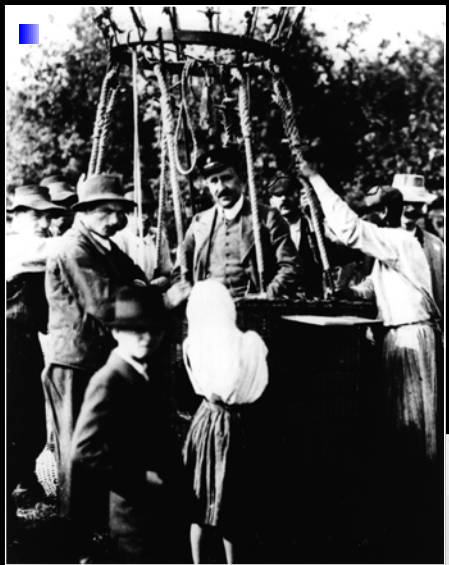

Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Electromagnetic
Weak
Strong
Universe
Technologies
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e-
Atom
Nucleus
p+
n
e+
μ-
π
τ-
p-
Particle zoo
νe
νμ
u
d
s
c
STANDARD MODEL
τ-
b
ντ
t
ν mass
5
6
Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
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
e+e- collider
Wire chamber
Beam cooling
Online computers
p+p- collider
Modern detectors
WWW
GRID

Universe

1913

In 1913, first hints of a violent universe appeared

Discovery of cosmic rays



Victor Hess

Hess

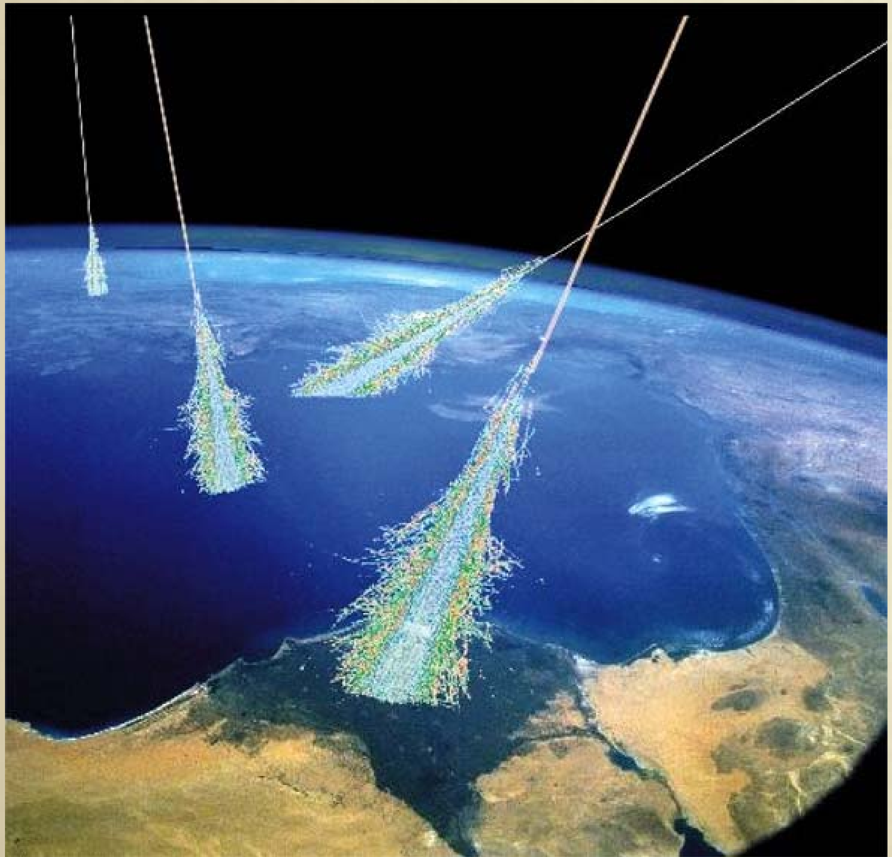
μ⁻

PARTICLE SPECTRUM

1937

After Yukawa's prediction of a 'pion' (1934), everybody was searching for this particle (100-200 MeV).

There was no accelerator with sufficient energy available (yet). So physicists went on mountain tops to search for tracks in their photographic emulsions.



A new particle was discovered in the right mass range

But: very long range in matter !! ?

That means: no (strong) interaction with nuclei, and therefore not Yukawa's pion !

Muon - 'heavy electron' (206 x m_e)

I. Rabi: "WHO ORDERED THAT ?"

PARTICLE SPECTRUM

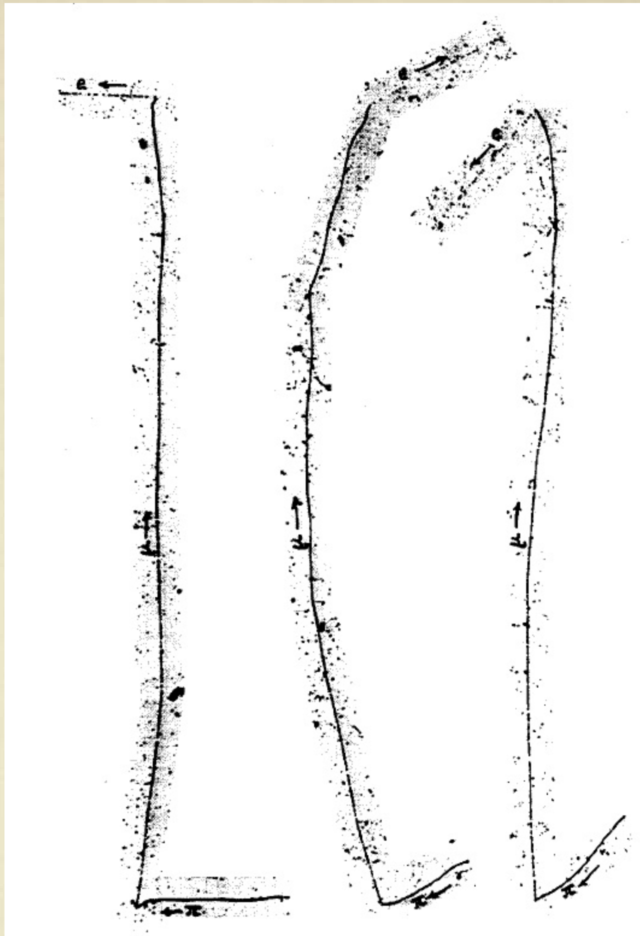
π

1947

Discovery of the (charged) pion

Cecil Powell

Ouff!



Photographic emulsion technique

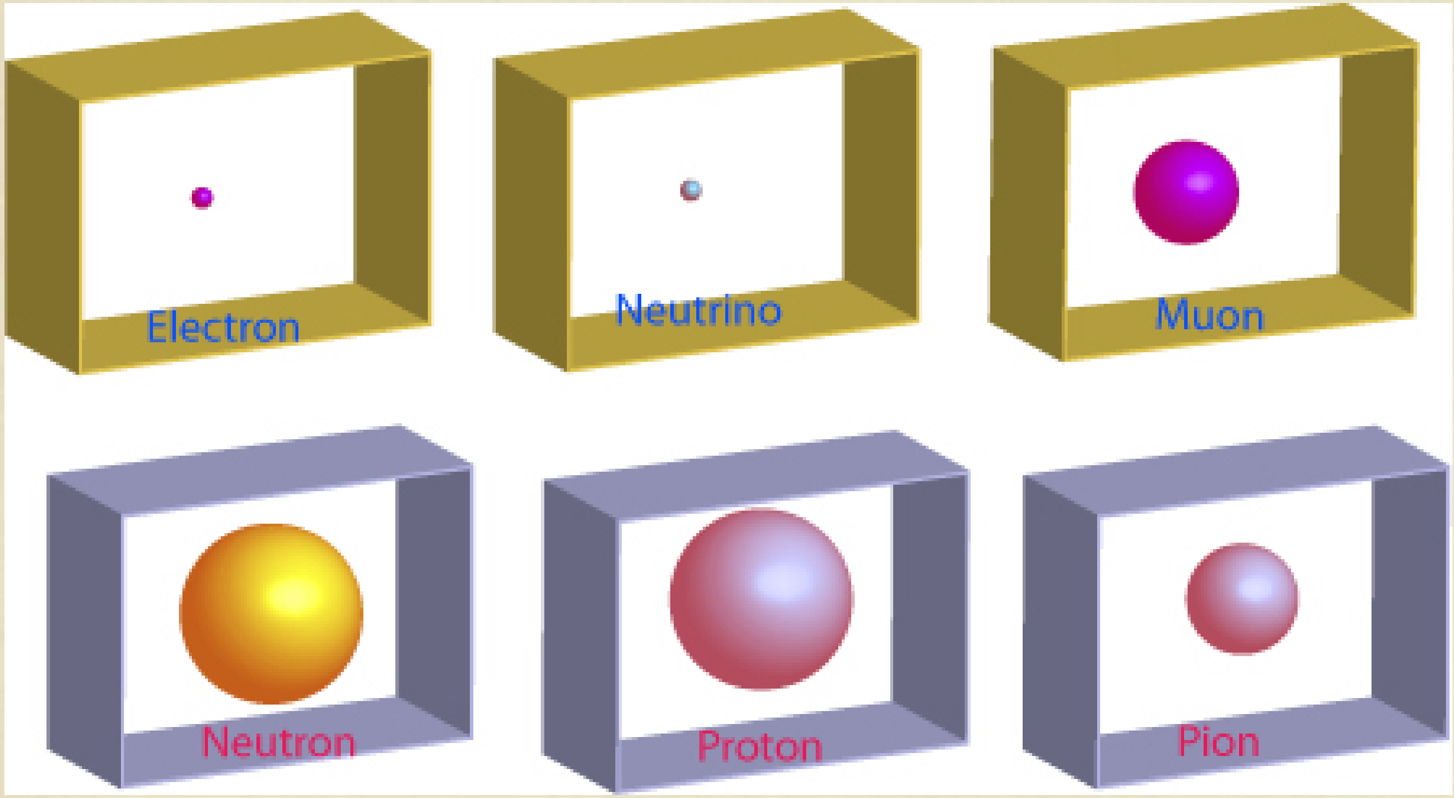
Cosmic rays at **high altitude** (Pic du Midi, Pyrenees)

Pion tracks identified under microscope

One year later: Pions produced at Berkeley cyclotron (Alpha+Carbon)

PARTICLE SPECTRUM

1948

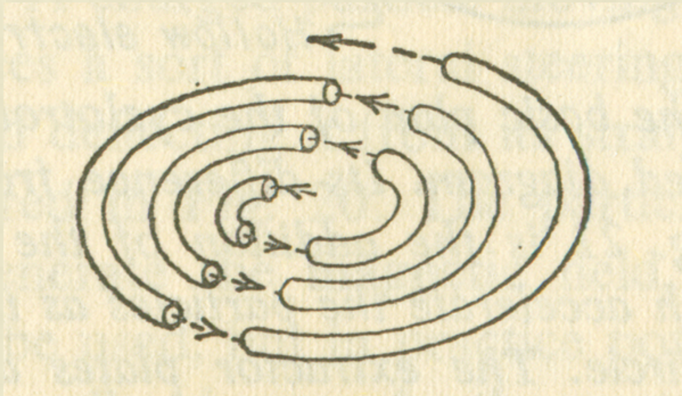


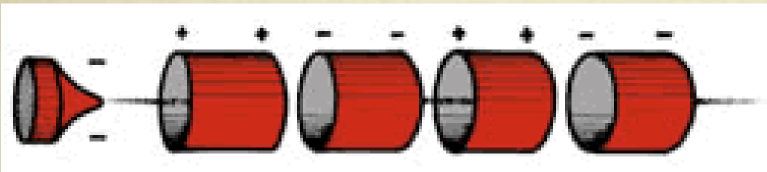
Accelerators

"Man-made cosmic rays"

Rolf Wideroe, 1928

Ernest Lawrence, 1931





Cyclotron

Linear accelerator

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

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

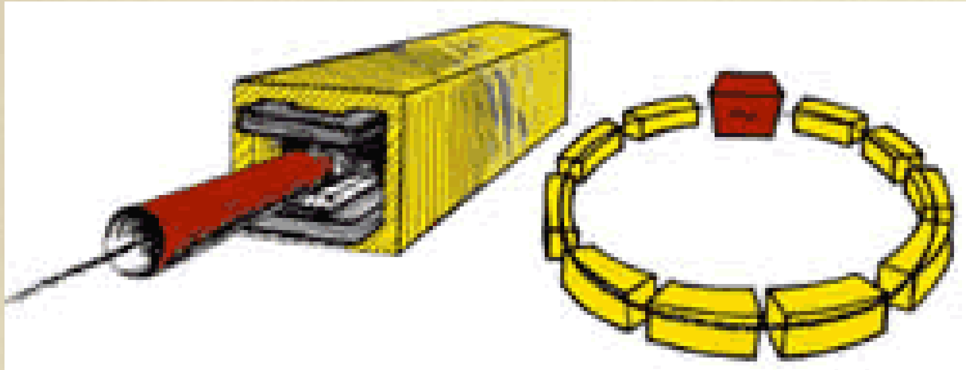
1931: 80 keV
1932: 1000 keV
1939: 19 MeV*
1946: 195 MeV ("synchrocyclotron")

* first limitations by relativistic mass increase

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

1950- 1968

Particl e zoo

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

Mesons

π^+ π^- π^0

Pions

K^+ K^- K^0

Kaons

η'

Eta-Prime

η

Eta

φ

Phi

ρ^+ ρ^- ρ^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 ?

SU(3) - Classification scheme based on ‘quarks’

Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

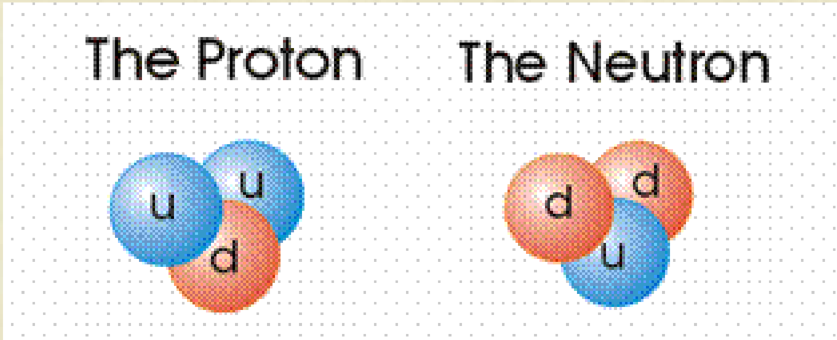
1) 3 types of “quarks” : up, down, strange

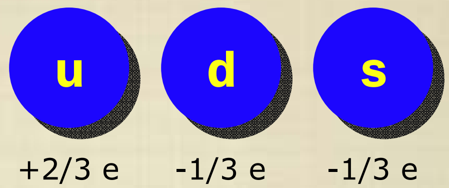
2) Carry electric charges: +2/3, -1/3, -1/3

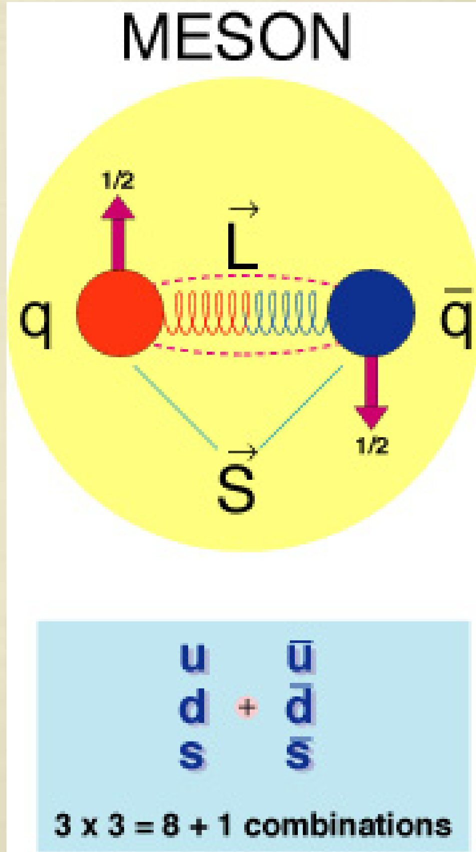
3) Appear in combinations:

Meson = quark+antiquark

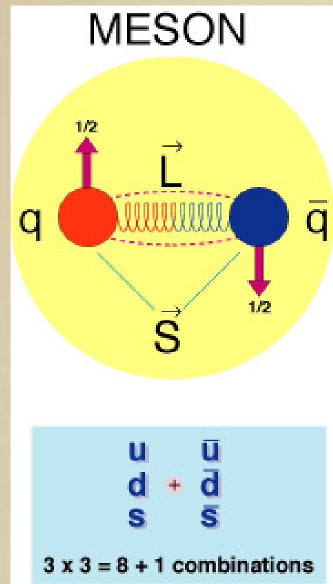
Baryon = quark(1) + quark(2) + quark(3)

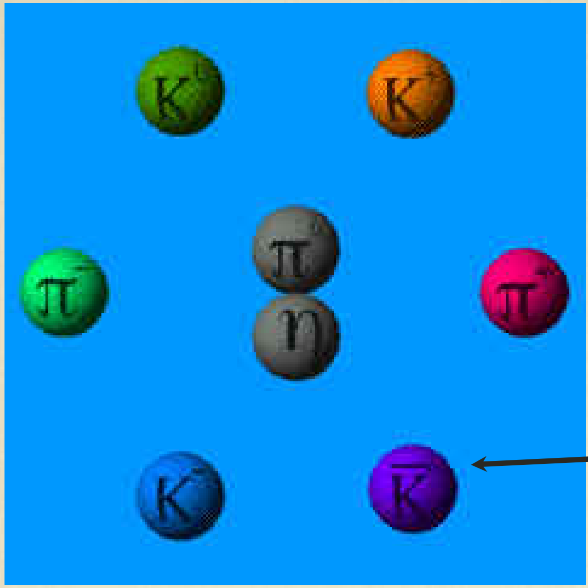






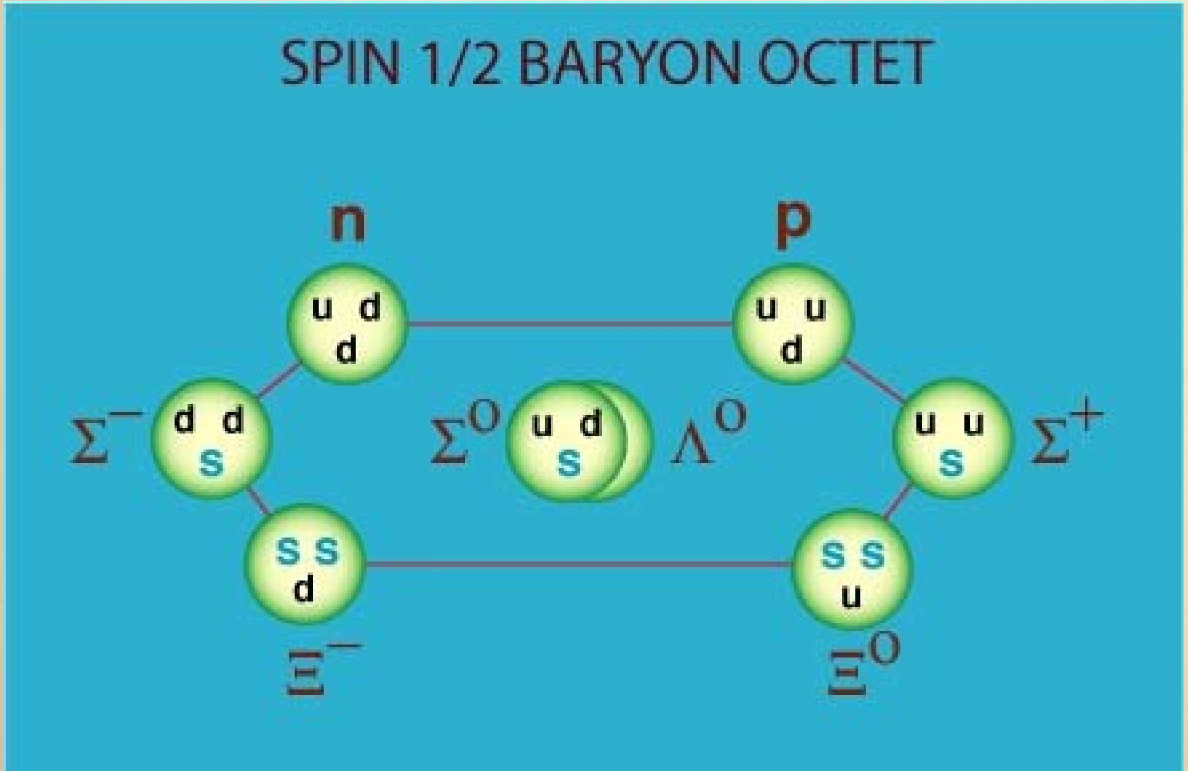
PARTICLE SPECTRUM





Pion, Eta-meson

Kaons have a strange quark

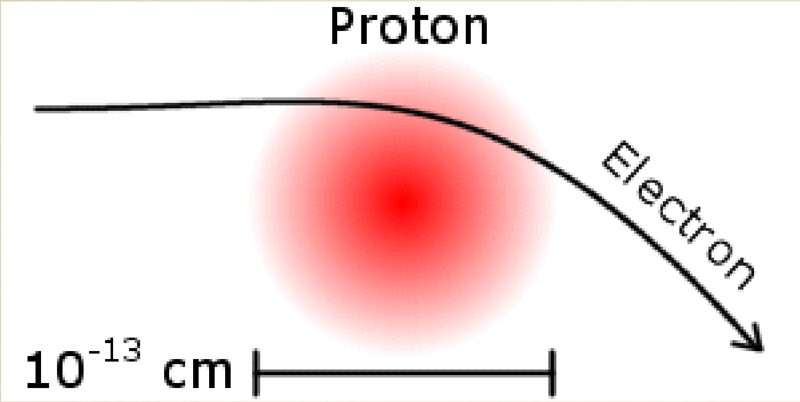


Ground state baryons:
Proton, Neutron;
Lambda, Sigma, Xi

PARTICLE SPECTRUM

Discovery of quarks

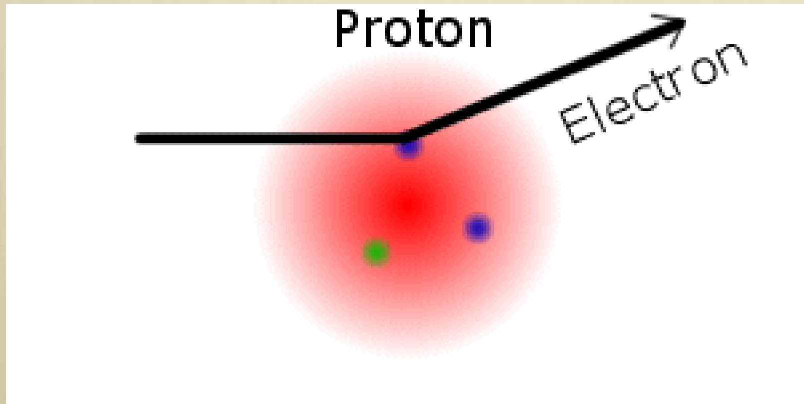
Electron-Proton scattering



1956 Hofstadter: measured finite proton radius

Stanford Linear Accelerator Centre

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

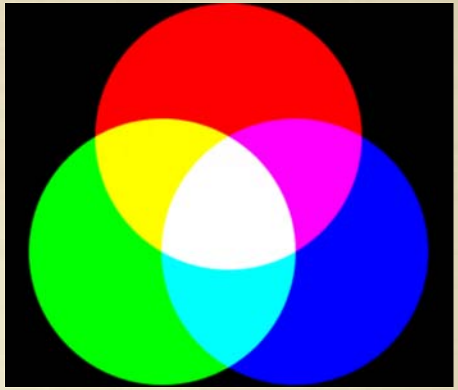


Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

PARTICLE SPECTRUM

1973

Colour charge



Δ^{++} three up-quarks with parallel spin, in a symmetric state

(u,u,u) *But: three fermions not allowed to be in identical states (Pauli exclusion principle)*

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

(Bardeen, Fritzsch, Gell-Mann)

Only colour-neutral bound states are allowed

MESONS = Quark-Antiquark

BARYONS = 3-Quark states

Positive pion

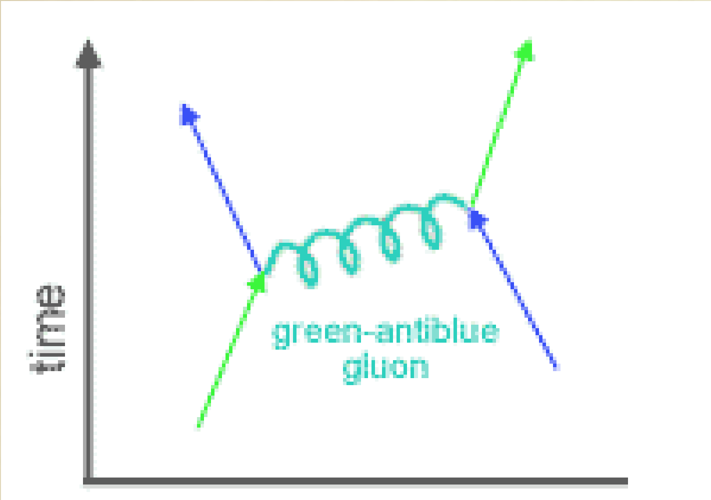
Colour-force transmitted by (eight) gluons

GLUONS CARRY COLOUR CHARGE - SELF-INTERACTION !

PARTICLE SPECTRUM

1973

Gluons

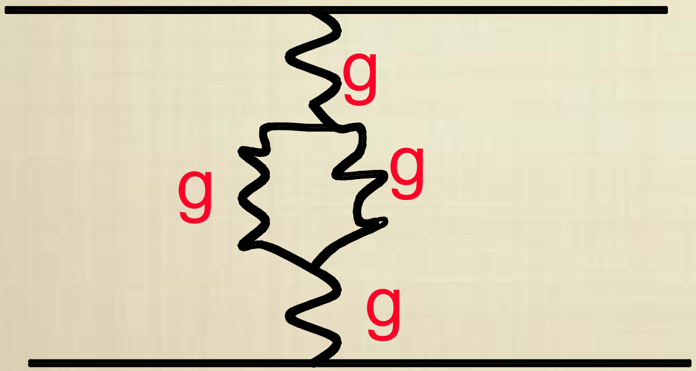


Gluons are massless carriers of the strong force

There are 3 x 3 - 1 = 8 different gluons

Gluons carry colour charge -> self-interaction

Self-interaction of gluons



Potential rises linearly with distance (for large r)

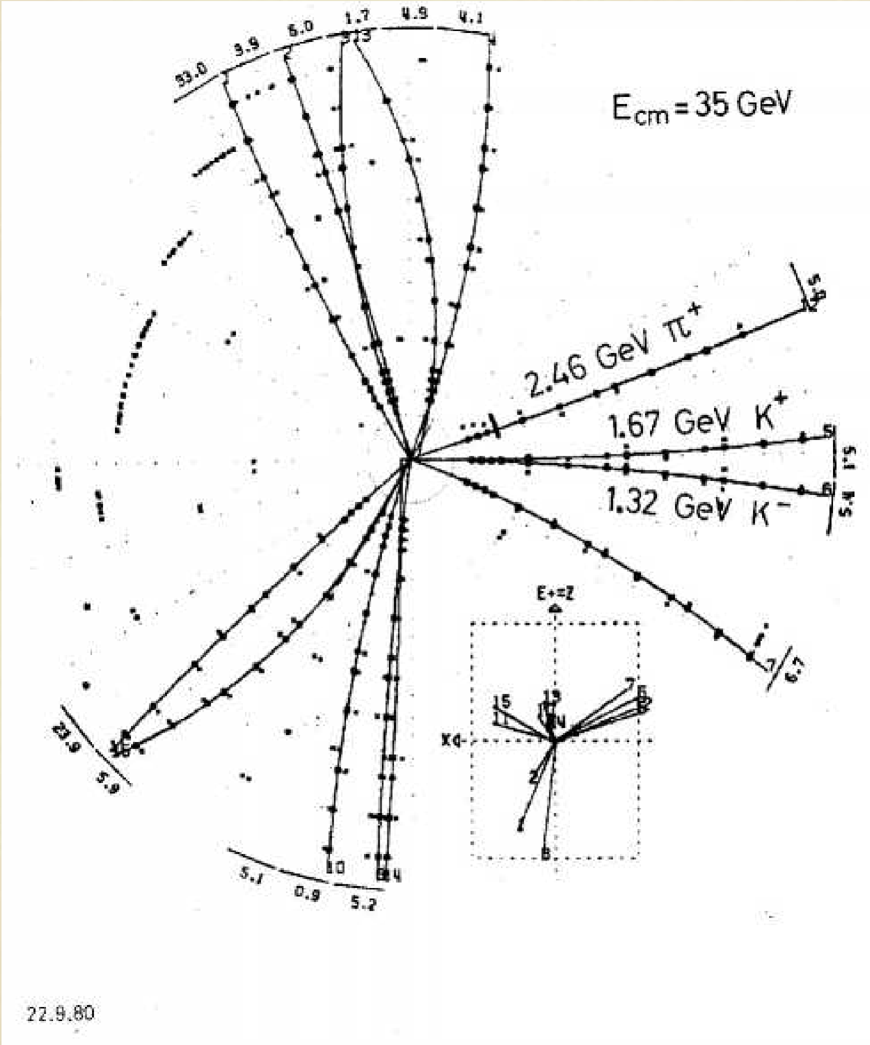
$$V_{QCD} = -\tfrac{4}{3}\frac{\alpha_s}{r} + kr$$

Small distances: asymptotic freedom

PARTICLE SPECTRUM

1973

Discovery of Gluons



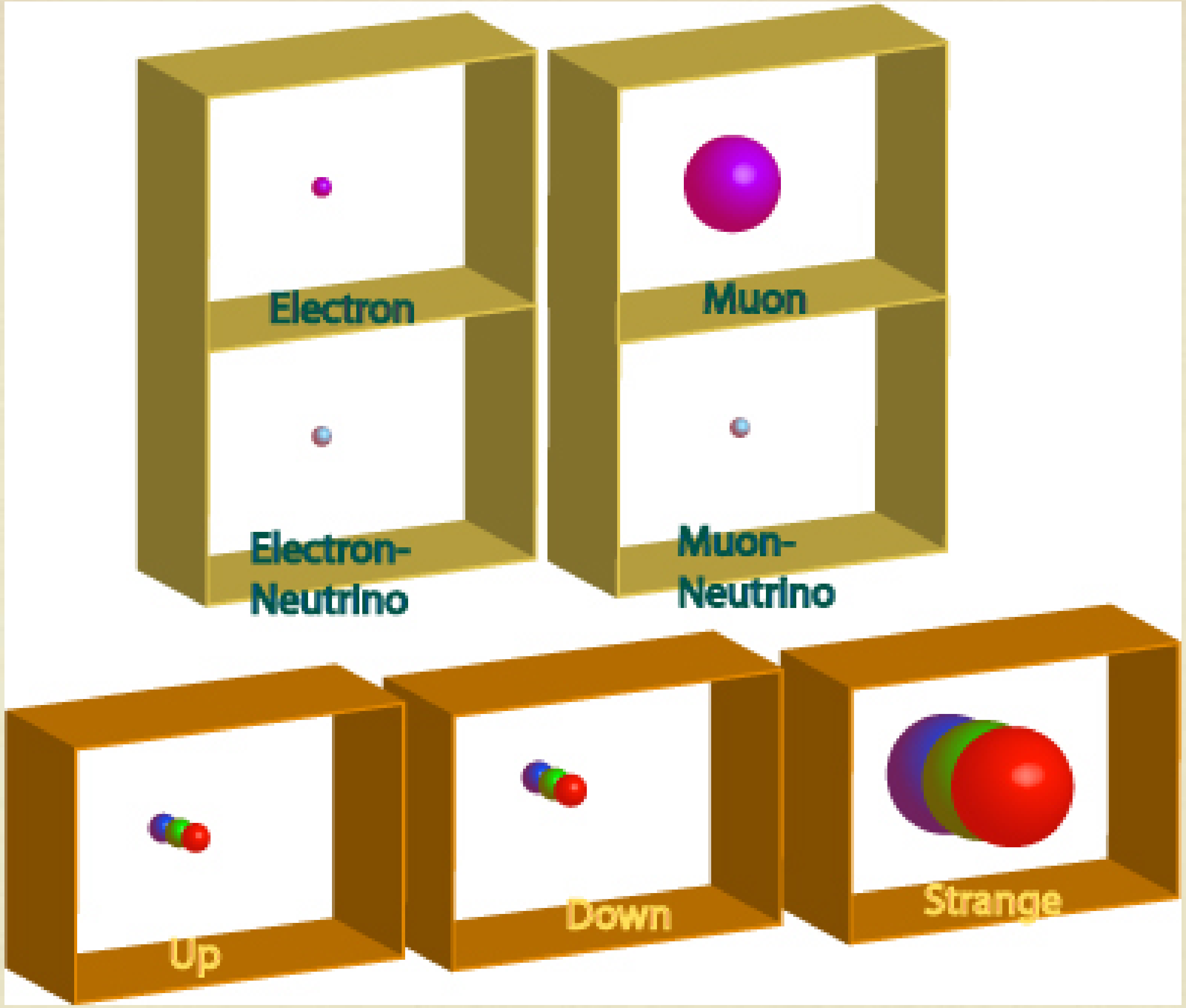
PETRA Storage Ring, 1979, DESY (Hamburg)

PARTICLE SPECTRUM

1973

LEPTONS

QUARKS



Connection?

KEY: 'electroweak' interaction and the 'flavour' of elementary particles

Fields

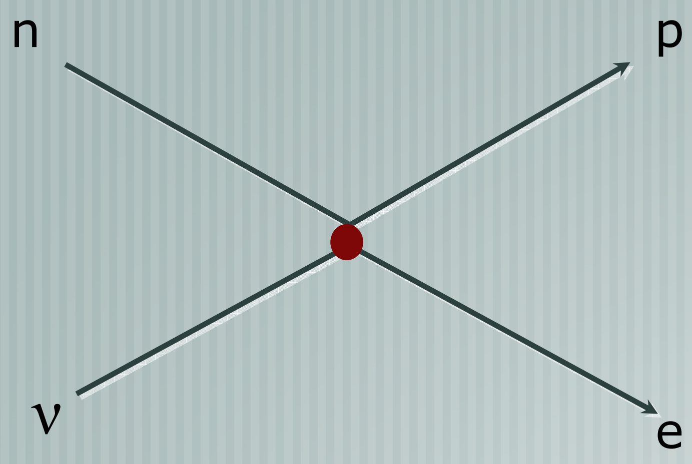
Electroweak Interaction

1958 Glashow

There was a big (theoretical) problem:
Neutrino-Proton cross-section ~ ($G_F E_\nu$)
violates conservation of probability* for E > 300 GeV

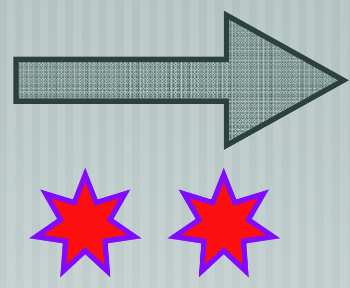
$G_F = (1/294\ \mathrm{GeV})^2$

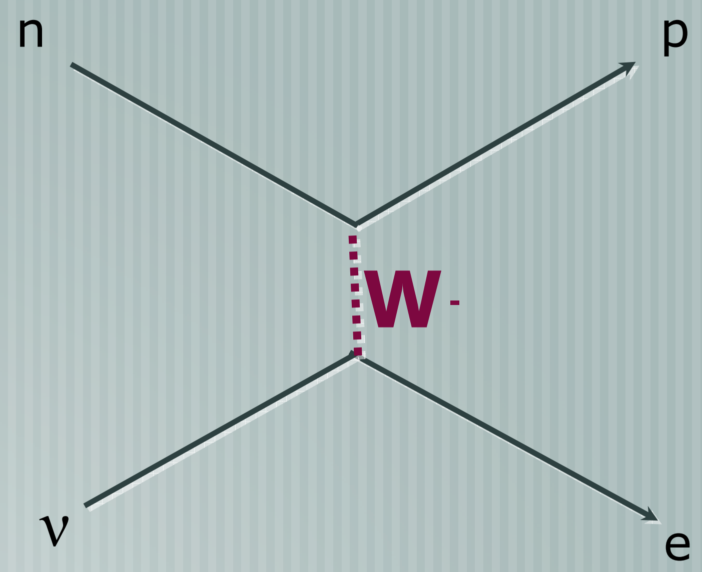
(the probability of the interaction becomes > 100%)



Fermi model

New Idea

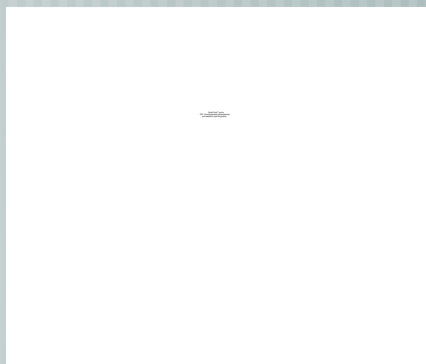




Glashow model

Weak interaction transmitted by massive vector bosons
(in analogy to photon exchange!)

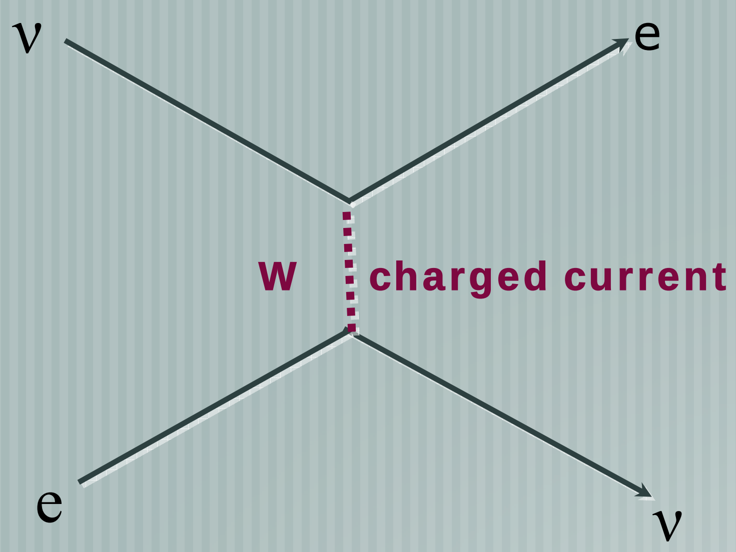
Large mass (80 GeV) explains
short range ($2\cdot10^{-18}$ m) and small cross-sections

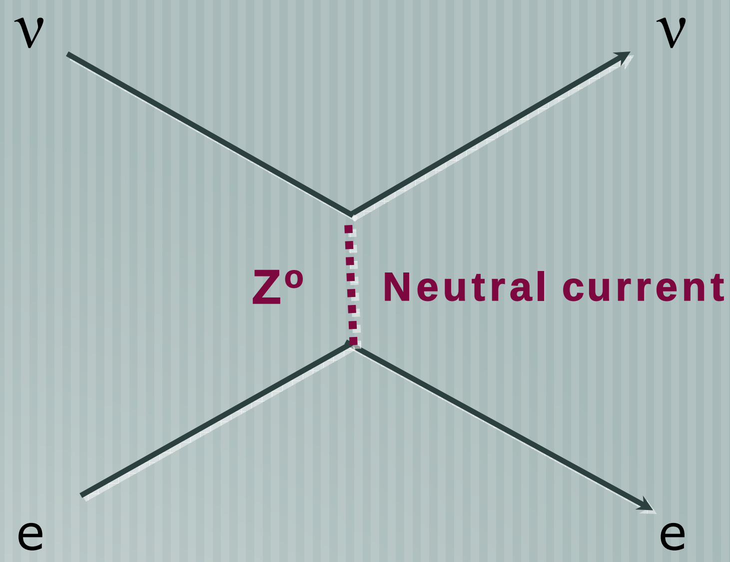


Fields

Electroweak Interaction

1968



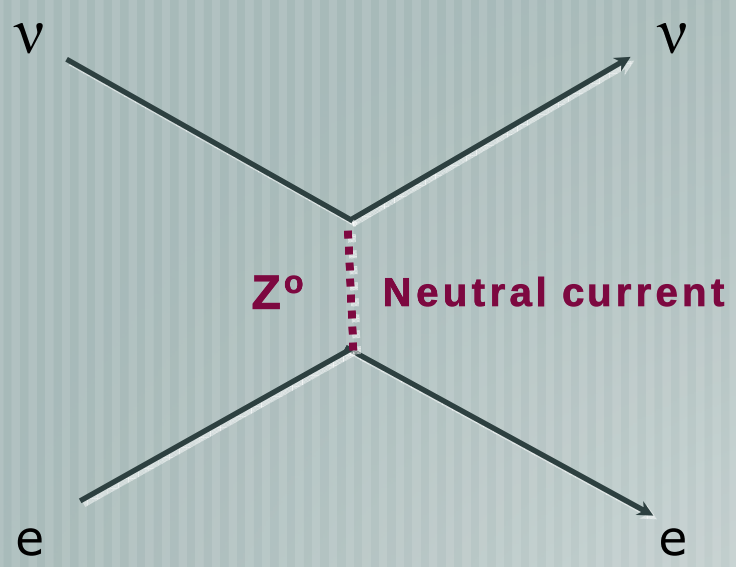


Glashow, Salam, Weinberg (1968) - Electroweak Force

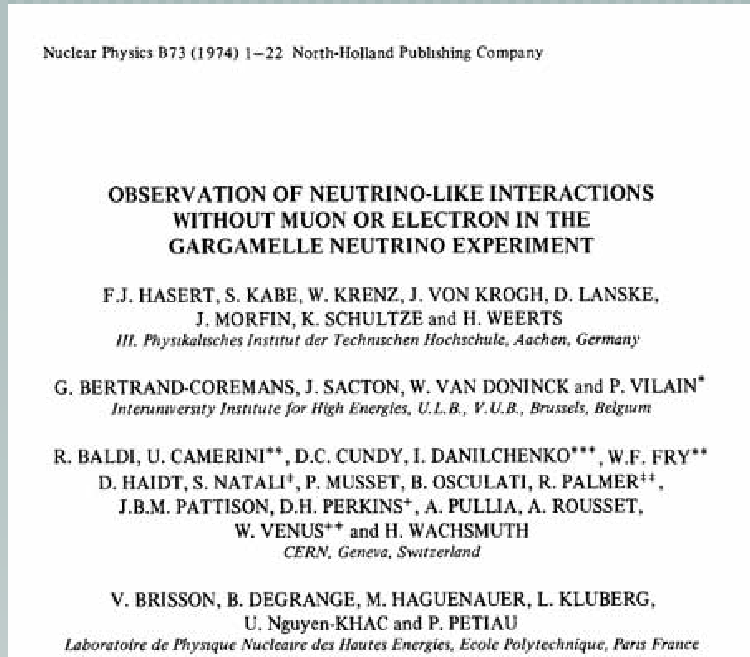
- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^o) and two charged vector boson ($W^{\pm}$) of mass ~ 50-100 GeV
- They acquire their mass by the interaction with the (new) "Higgs field" H.
- There are only 'left-handed' interactions

Fields

Discovery of neutral currents at CERN (1973)



- Neutrino beam directed on a bubble chamber
  - An electron track emerges out of 'nowhere'



Nuclear Physics B73 (1974) 1–22 North-Holland Publishing Company

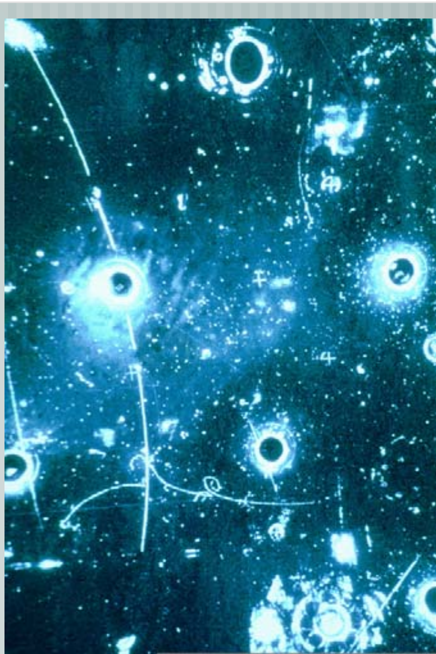
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. VON KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, J. SACTON, W. VAN DONINCK and P. VILAIN*
Interuniversity Institute for High Energies, U.L.B., V.U.B., Brussels, Belgium

R. BALDI, U. CAMERINI**, D.C. CUNDY, I. DANILCHENKO***, W.F. FRY**
D. HAIDT, S. NATALI‡, P. MUSSET, B. OSCULATI, R. PALMER‡‡,
J.B.M. PATTISON, D.H. PERKINS+, A. PULLIA, A. ROUSSET,
W. VENUS++ and H. WACHSMUTH
CERN, Geneva, Switzerland

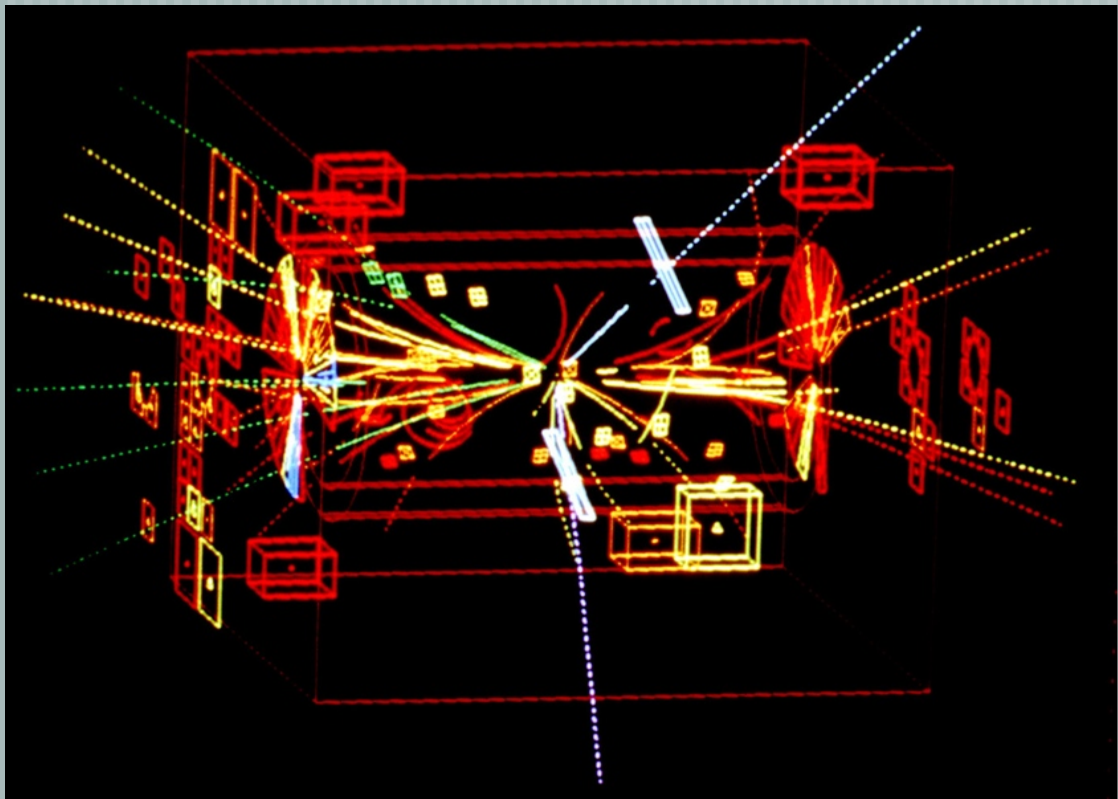
V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG,
U. Nguyen-KHAC and P. PETIAU
Laboratoire de Physique Nucleaire des Hautes Energies, Ecole Polytechnique, Paris France



Fields

Discovery of the W, Z bosons at CERN (1983)

(Carlo Rubbia - leader of UA1 collaboration, and proponent of proton-antiproton collider in SpS)
(Simon van der Meer - inventor of stochastic beam cooling)



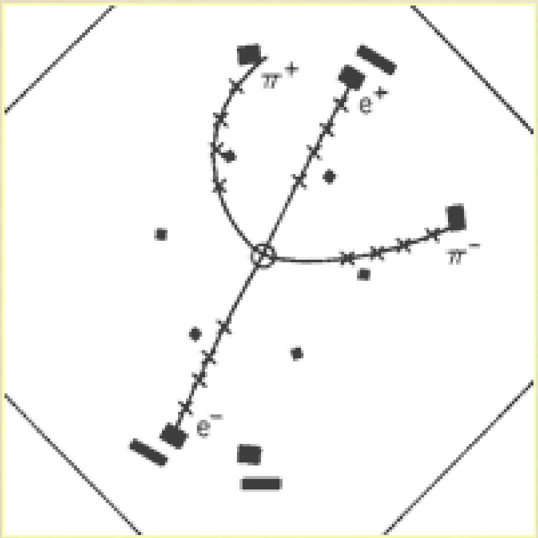
PARTICLE SPECTRUM

1974

And the charm quark was to be discovered soon afterwards :

The NOVEMBER REVOLUTION (11 November 1974)

Two groups discovered ~ simultaneously a new particle, which they called **'Psi'** at SLAC (Burt Richter) and '**J**' at Brookhaven (Sam Ting).



EW LETTERS 2 DECEMBER 197

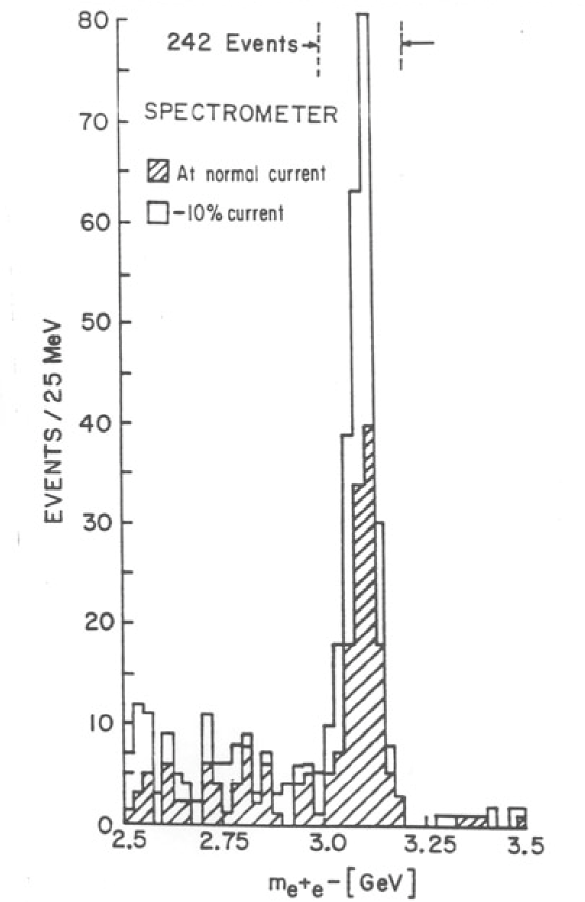


FIG. 2. Mass spectrum showing the existence of *J*. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

The J/psi resonance was 'long-lived' (~10^{-20} sec). It could only decay by weak interactions, preferably into an s-quark. This explains the narrow peak.

Fields

Milestone paper (Glashow, Iliopoulos, Maiani)

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

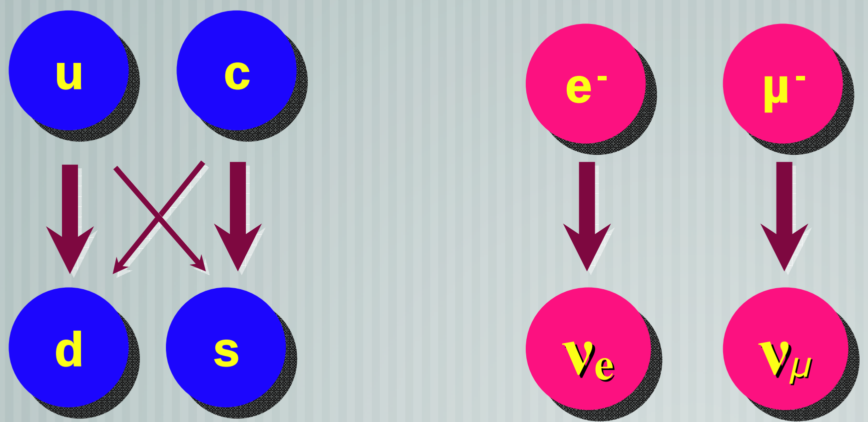
Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Quarks Leptons



This was now called the 'Standard Model' (with two families)