QUALI-STARTUP LECTURES

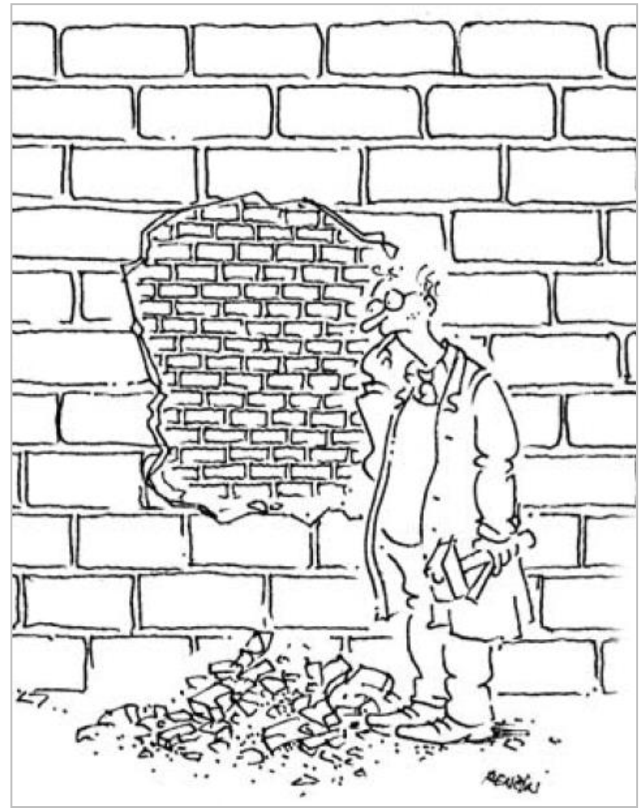
A BRIEF INTRODUCTION INTO STRUCTURE-OF-MATTER

SEPTEMBER 9, 2019 I HANS STRÖHER

Mitglied der Helmholtz-Gemeinschaft

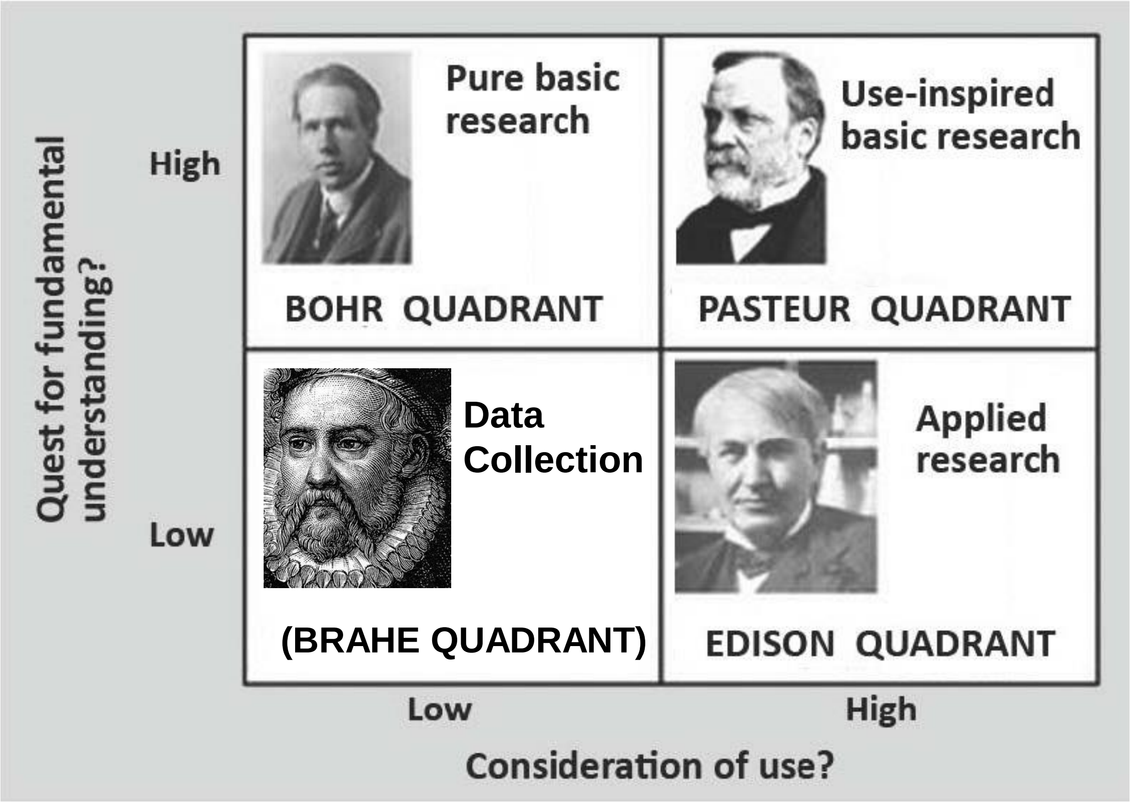
JÜLICH Forschungszentrum

Introduction – Prelude



Science is driven by curiosity

Introduction – Prelude



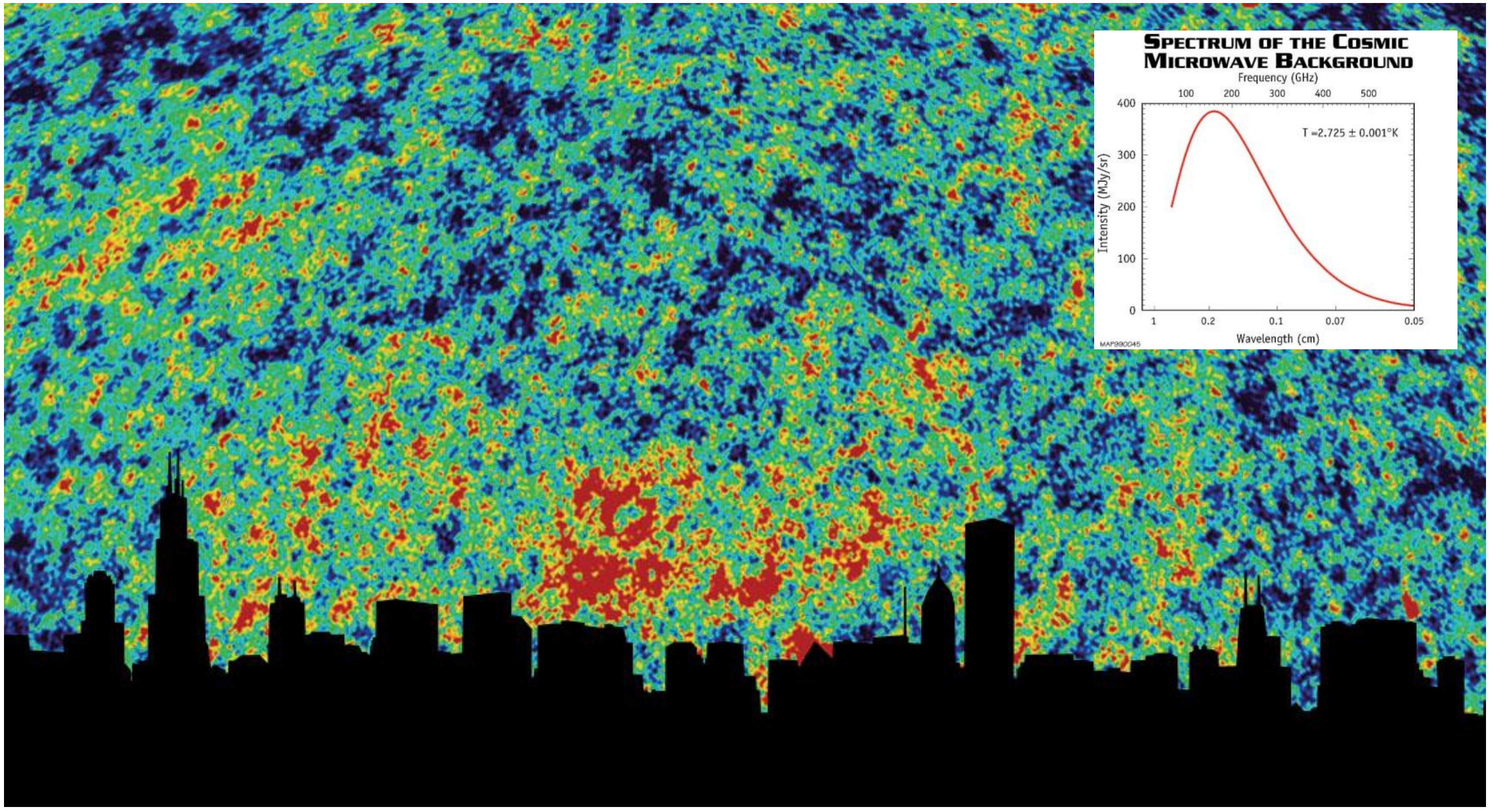
Curiosity-driven *vs.* use-inspired (basic) research

Introduction – Prelude

The *Milky Way* over monument valley

Mankind strives to understand **Nature** – from the very large …

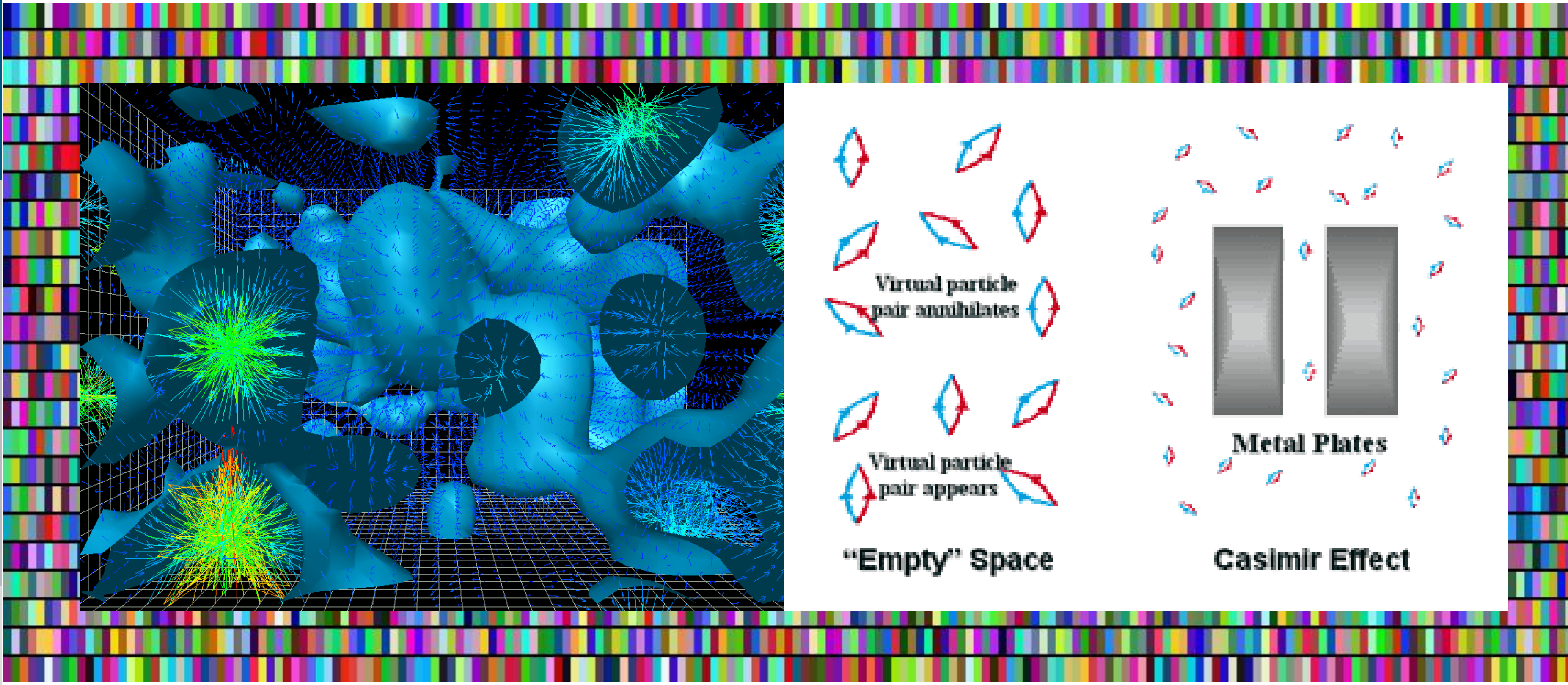
Introduction – Prelude



The *Cosmic Microwave Background* (CMB)

Mankind strives to understand **Nature** – from the very large …

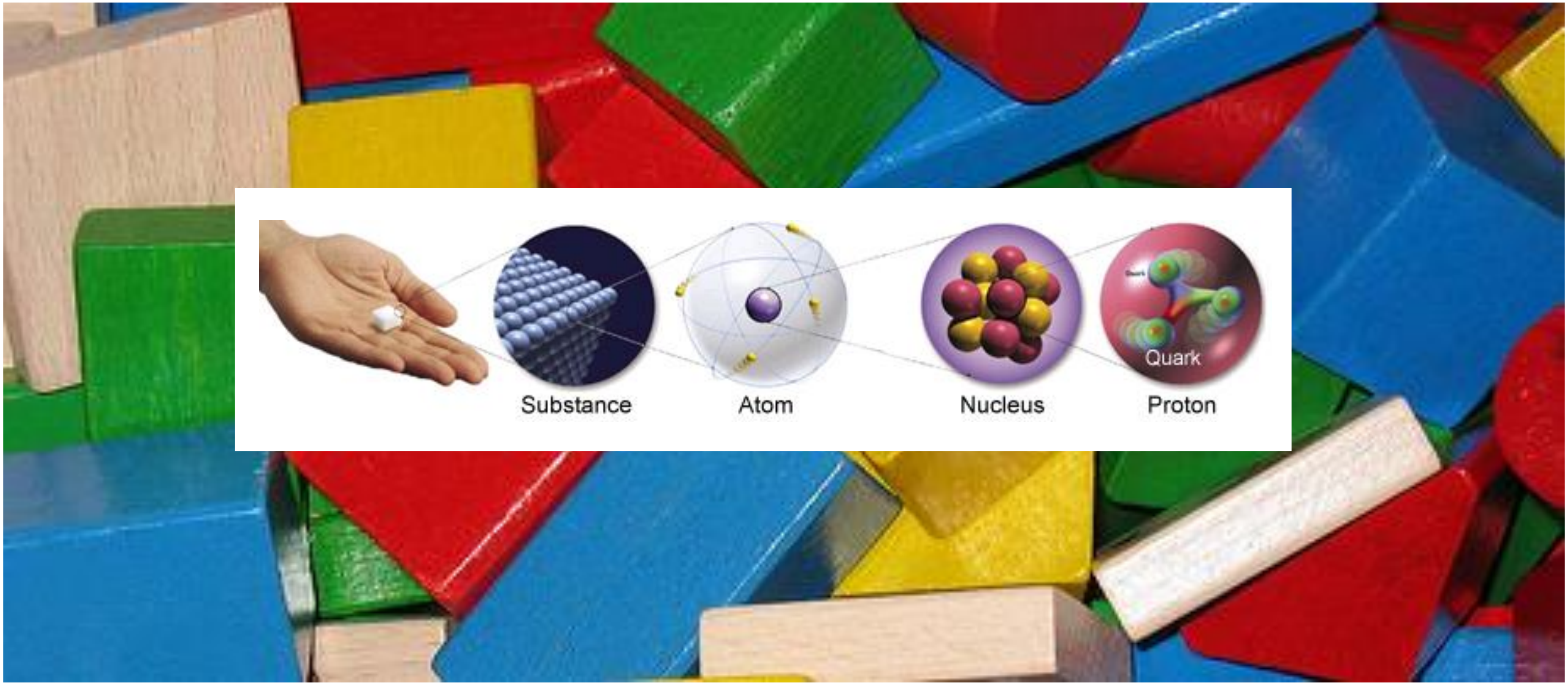
Introduction – Prelude



***Vacuum Fluctuations* (Simulation)**

Mankind strives to understand **Nature** – from the very large to the very small

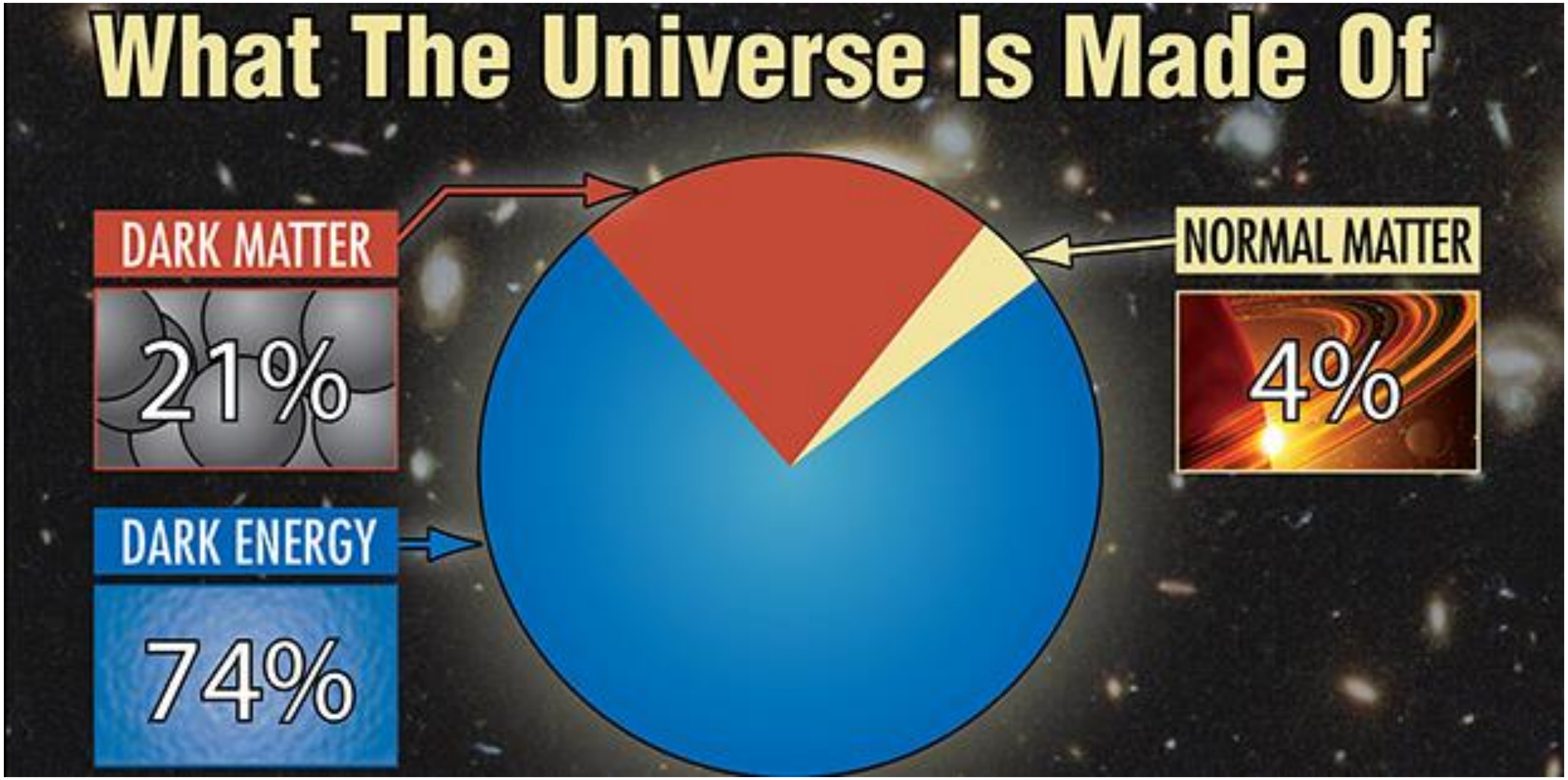
Introduction – Prospect



The building blocks of matter

There is a **connection** between the *very large* and the *very small*

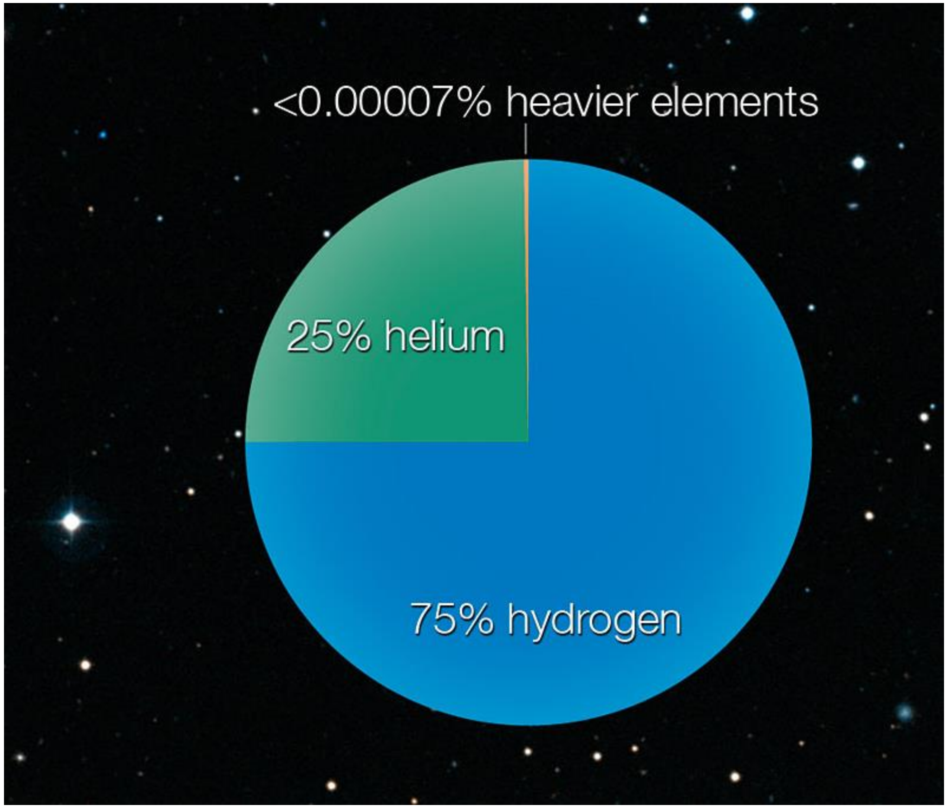
Introduction – Prospect



What we know and what we don´t know

This talk is only about a **tiny fraction** of the energy content of the Universe

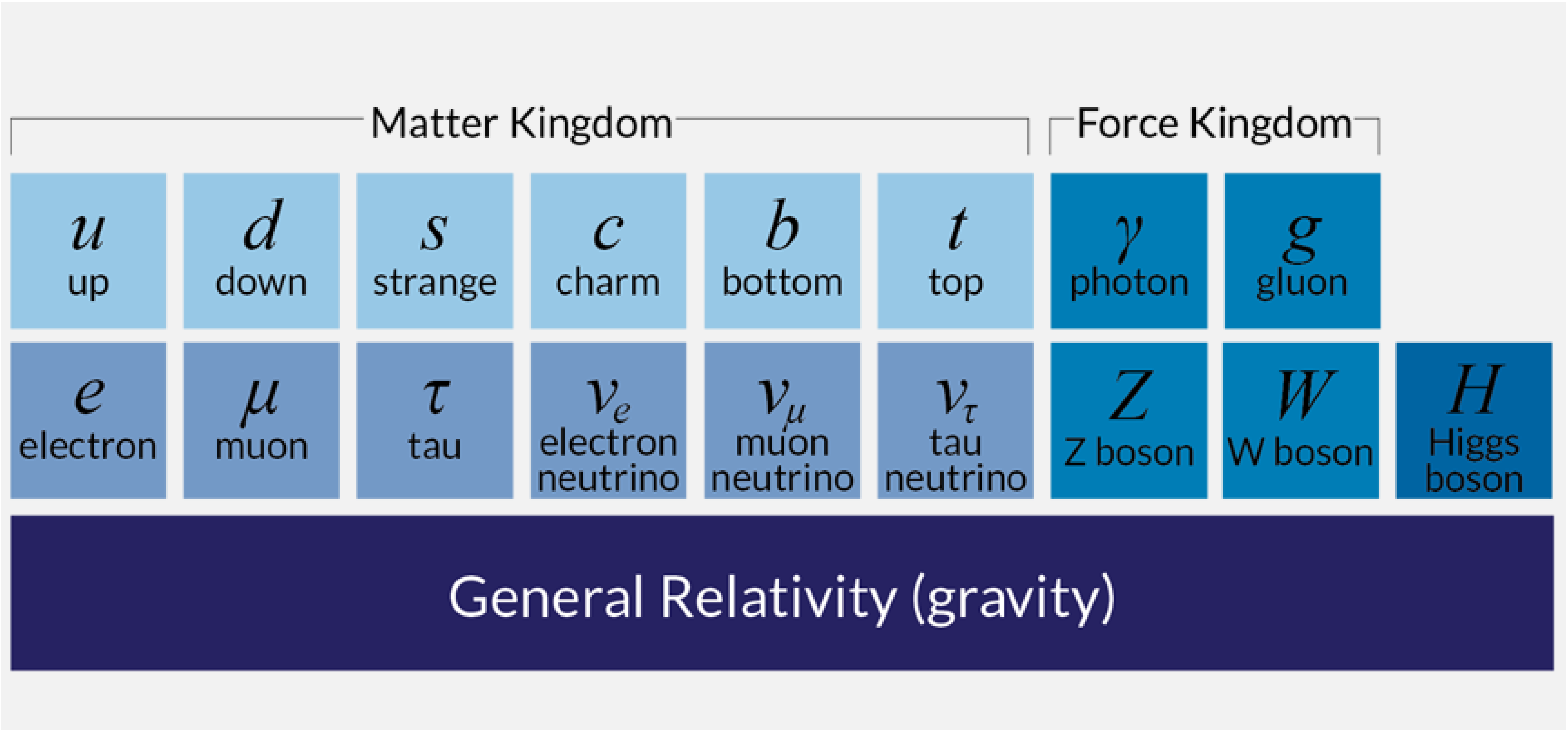
Introduction – Prospect



What we know and what we don´t know

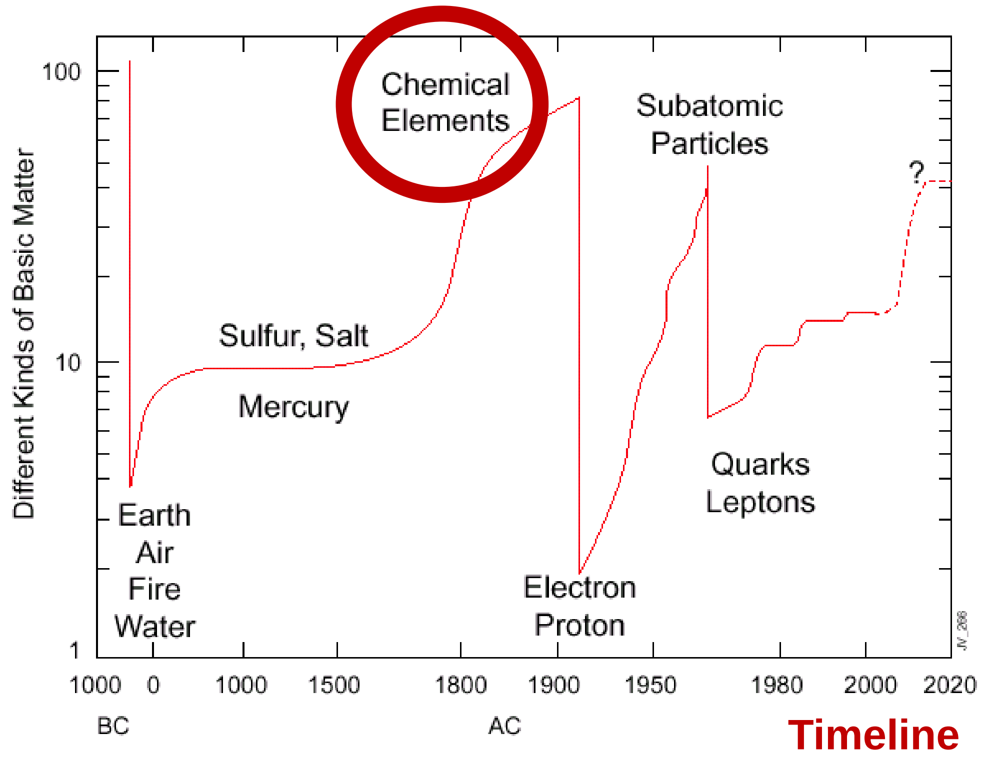
Matter is **essentially hydrogen** and helium (+ a tiny fraction of heavy nuclei)

Introduction – Prospect



F. Wilczek (Nobel Laureate Physics 2004): „**Core Theory**" of physics

Introduction – History



A historical account of the number of matter-constituents

Introduction – History

Key

Key
Atomic #
Symbol
Exact Name

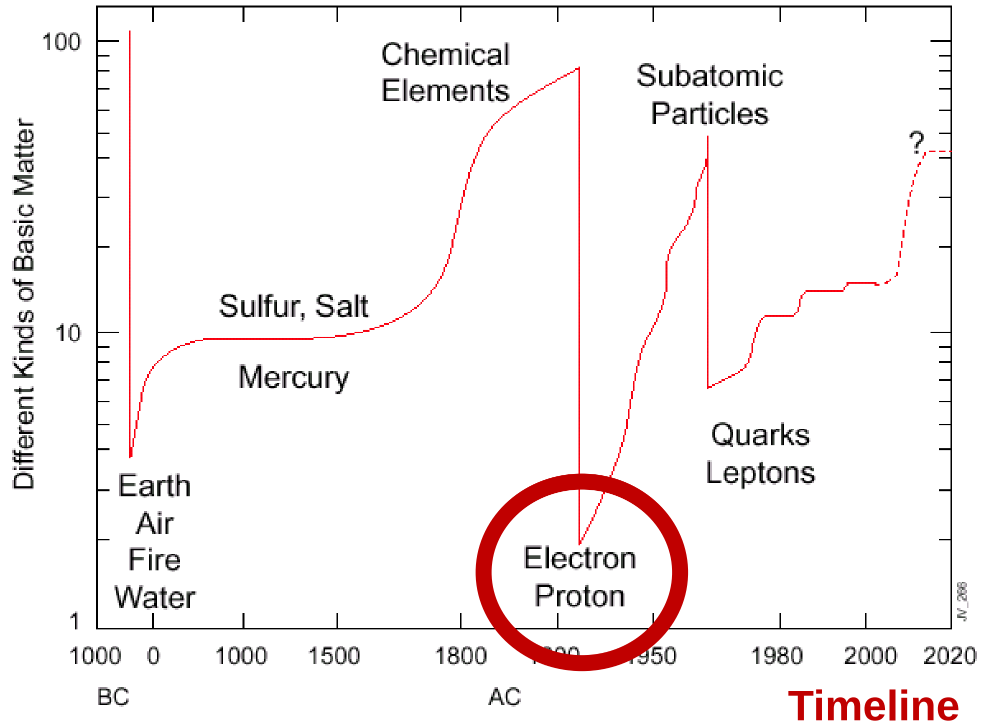
1 H Hydrogen																		2 He Helium
3 Li Lithium	4 Be Beryllium												5 B Boron	6 C Carbone	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium												13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium		21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium		39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	*	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	* *	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium		114 Fl Flerovium		116 Lv Livermorium		

*	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
* *	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium

Pauli-principle at work

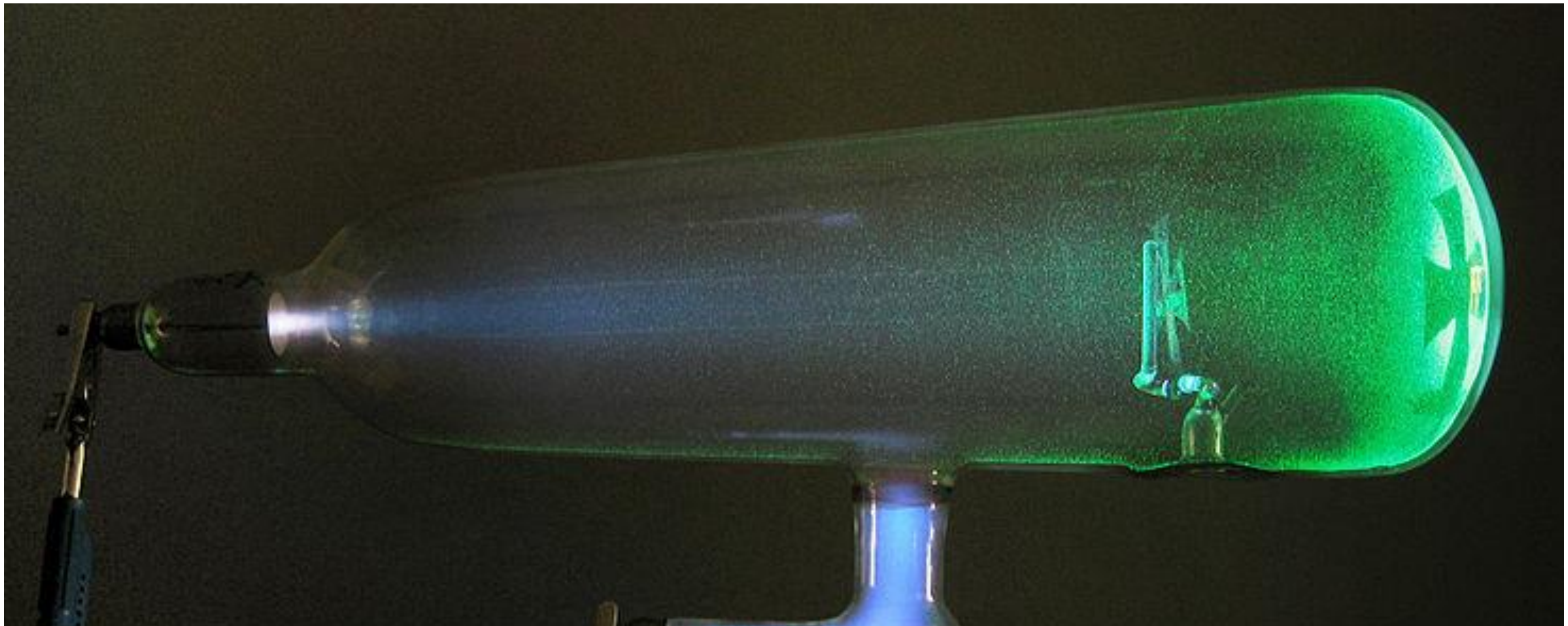
Periodic **Table of Elements**

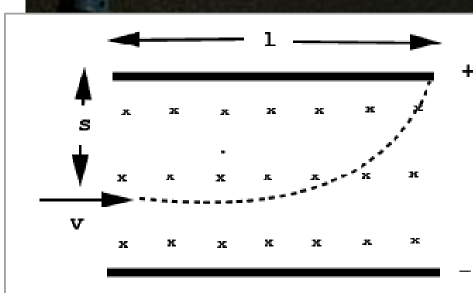
Introduction – History



The up´s and down´s in the number of matter constituents

Introduction – History



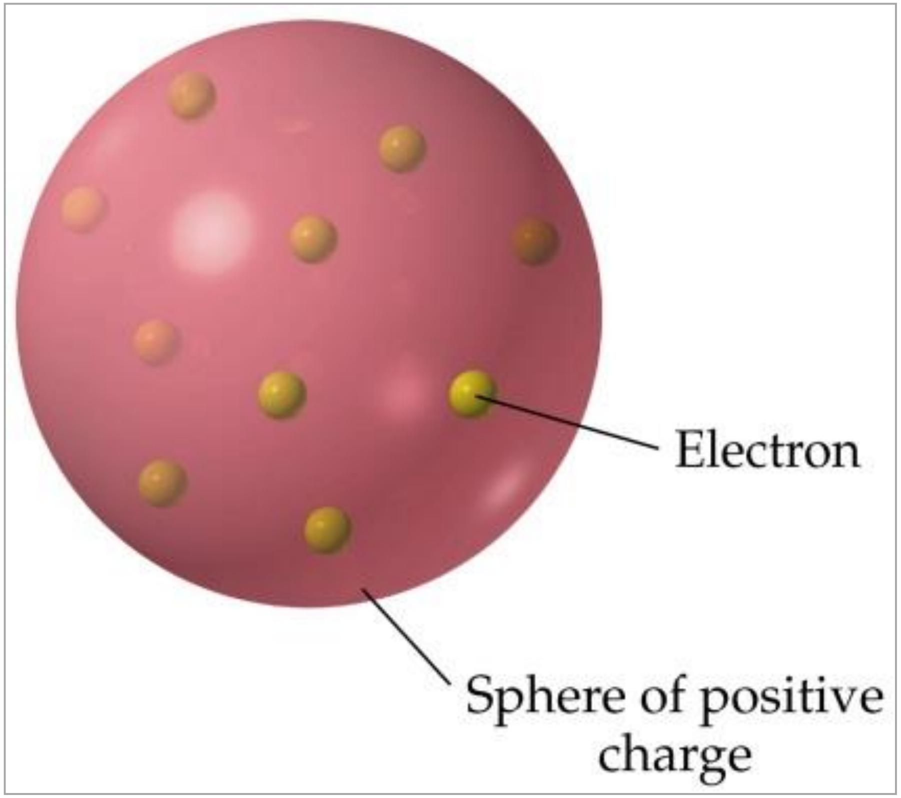


$$\frac{e}{m} = \frac{2sE}{l^2H^2}$$

$$\left[\frac{\text{The charge-to-mass ratio of cathode rays, } e/m}{\text{The charge-to-mass ratio of hydrogen ion}}\right] = \frac{1.76 \times 10^{11}}{9.65 \times 10^{7}} \approx 1800.$$

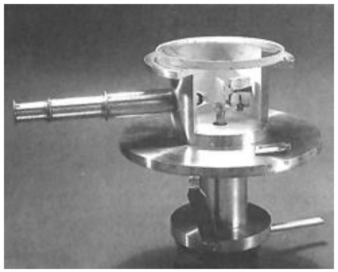
„Cathode rays" → discovery of the electron

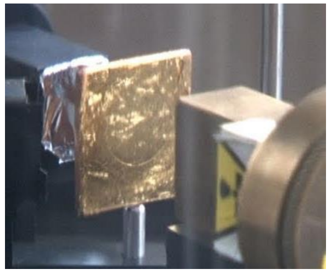
Introduction – History

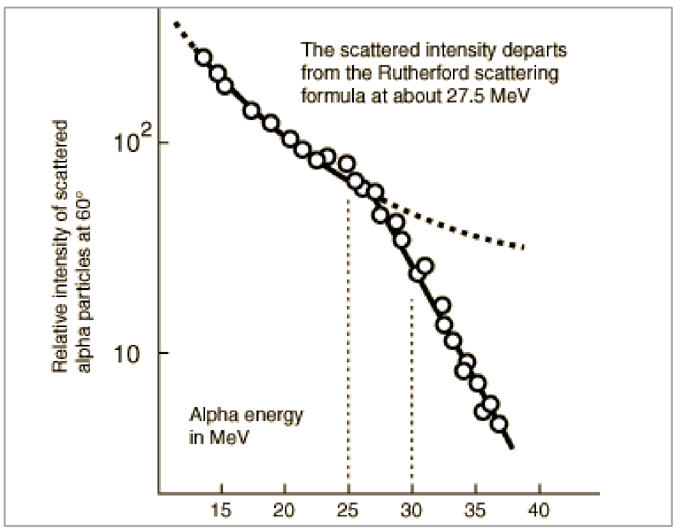


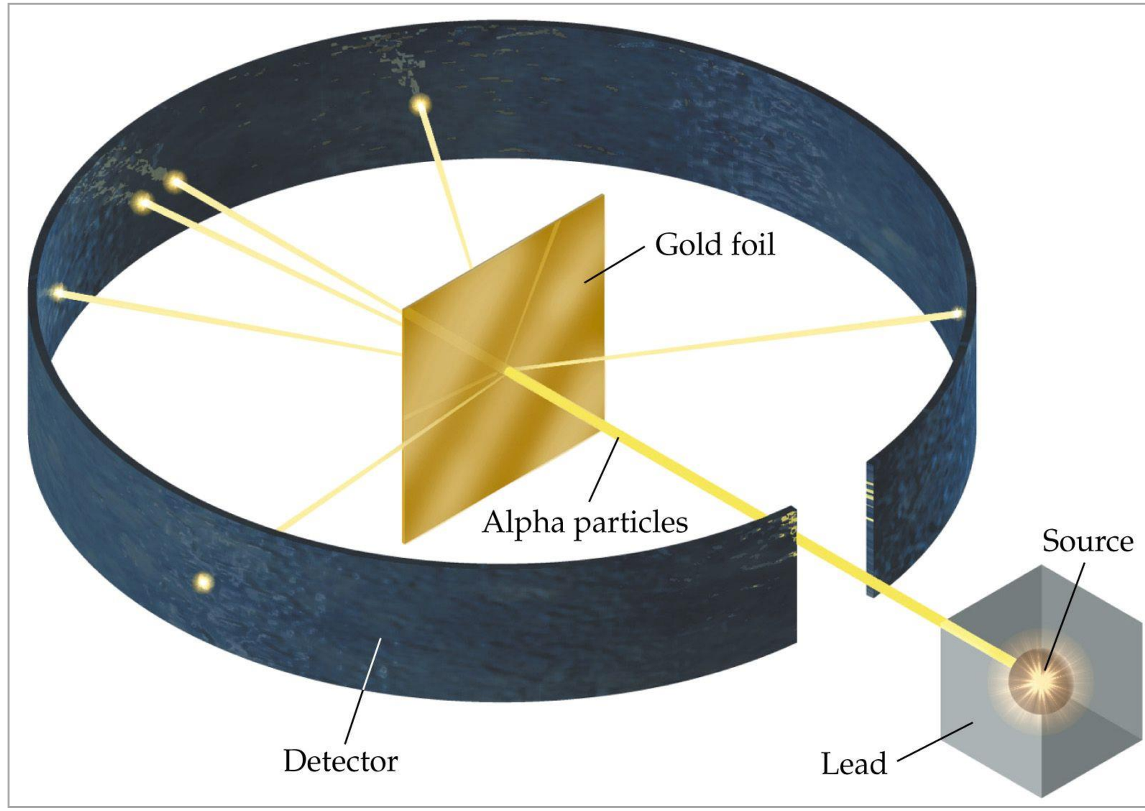
Discovery of the **electron** (J.J. Thomson, 1897) → Thomson´s atom-model

Introduction – History



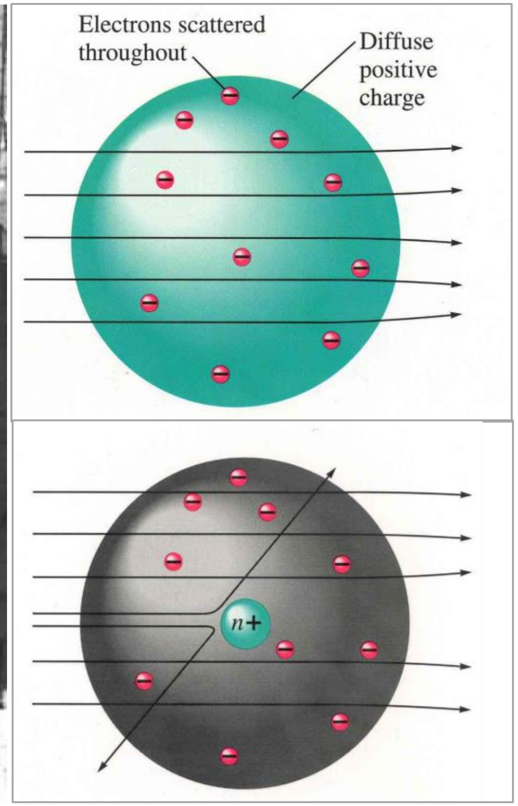


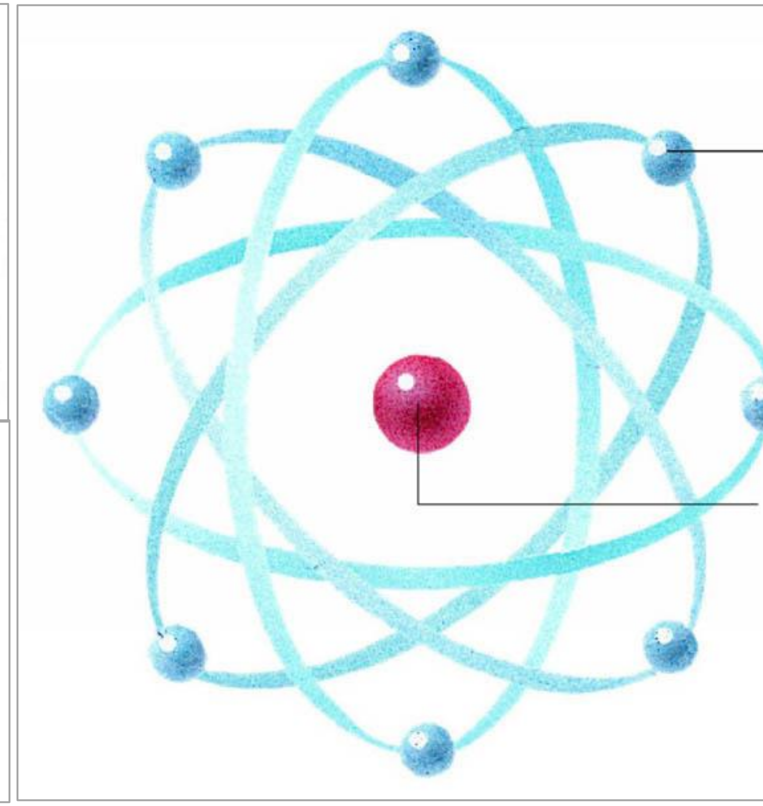




Discovery of the atomic nucleus (E. Rutherford, 1911) → new atomic model

Introduction – History





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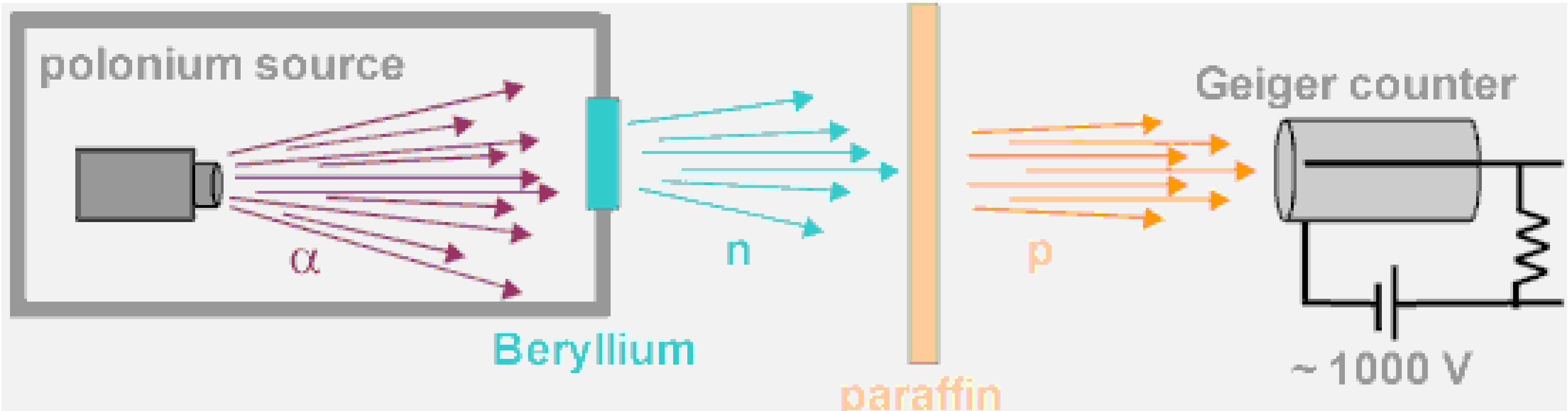
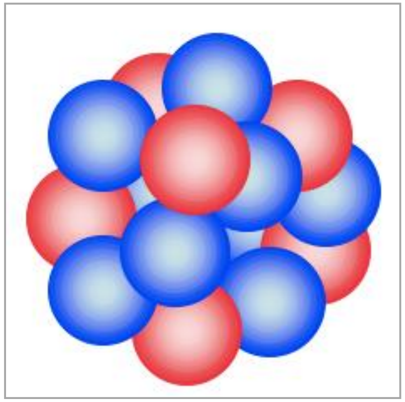
Introduction – History

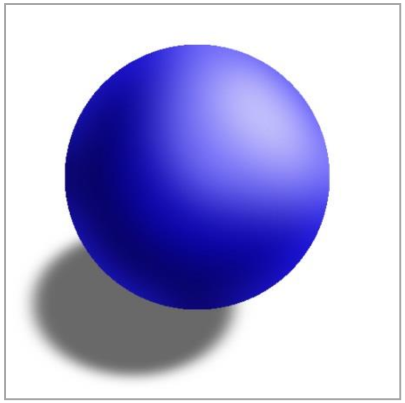


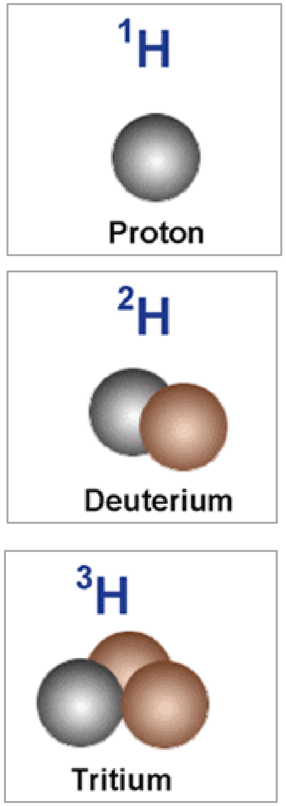
$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \longrightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} $$

Discovery of the **neutron** (J. Chadwick, 1932) → structure of the nucleus

Introduction – History

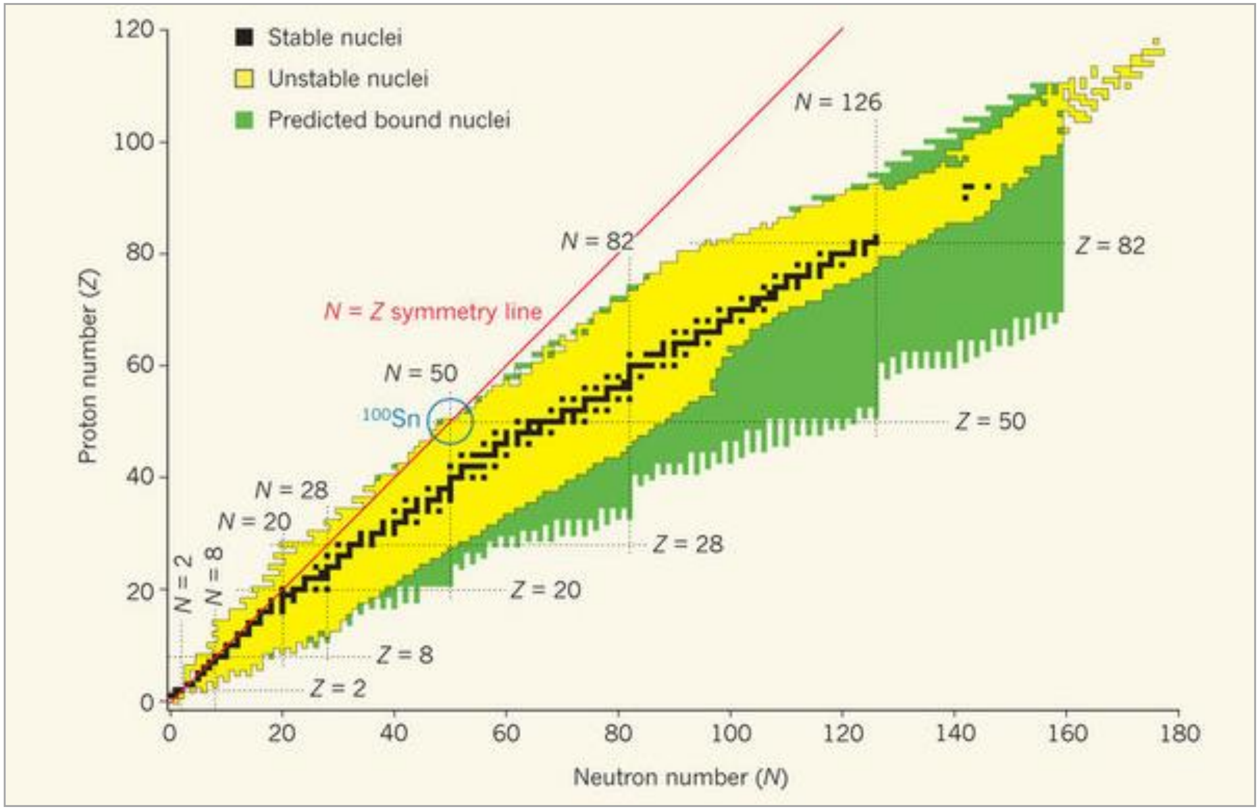






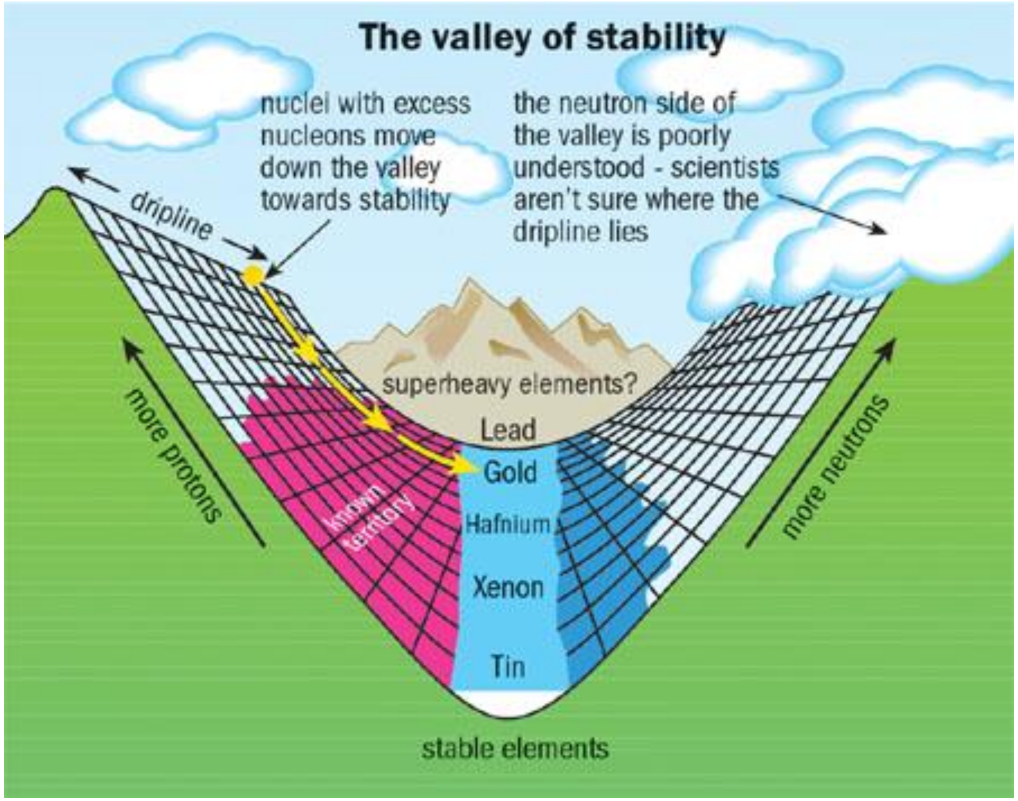
Discovery of the **neutron** (J. Chadwick, 1932) → isotopes

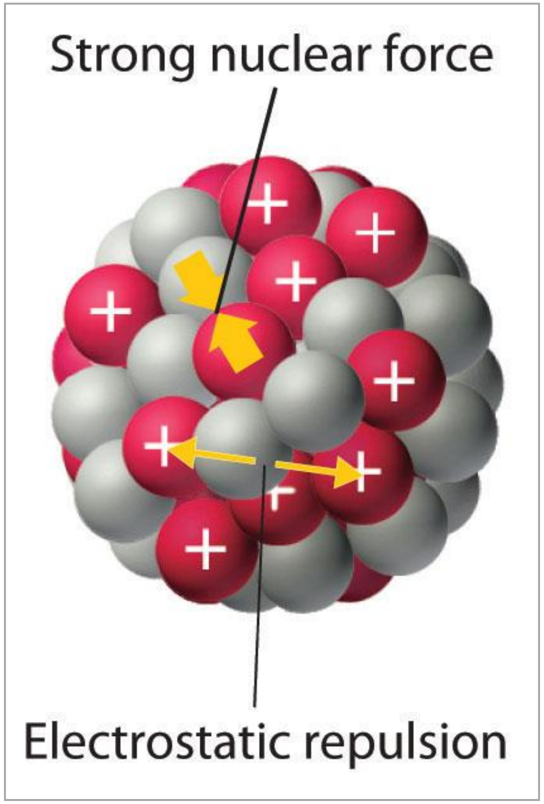
Introduction – History



The „Table of Isotopes“

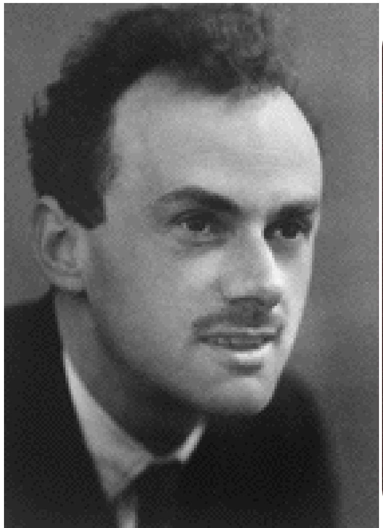
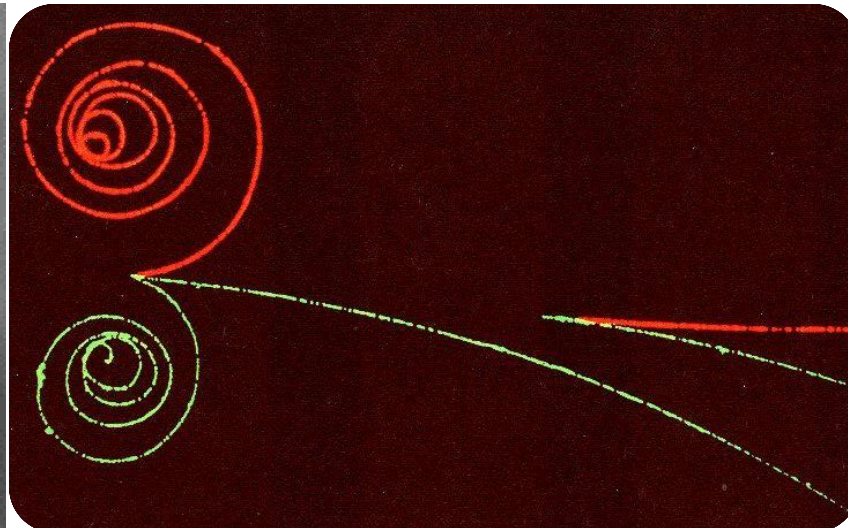
Introduction – History

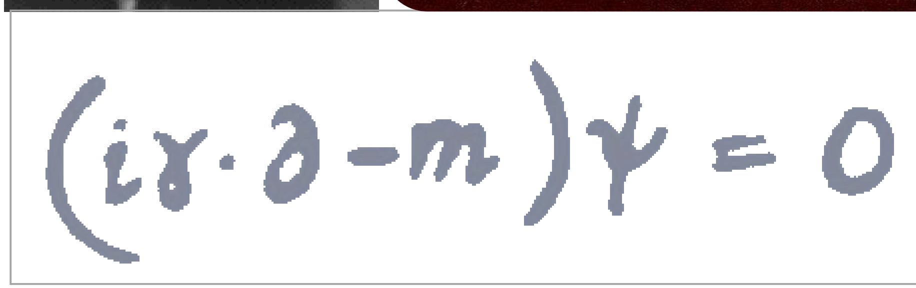


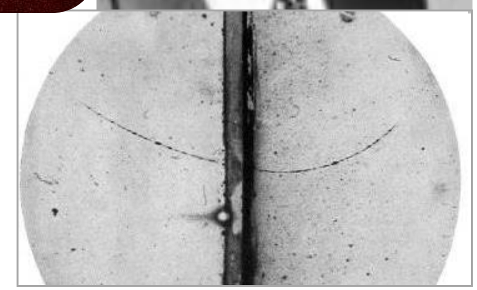


The „**Valley of Stability**“

Introduction – History

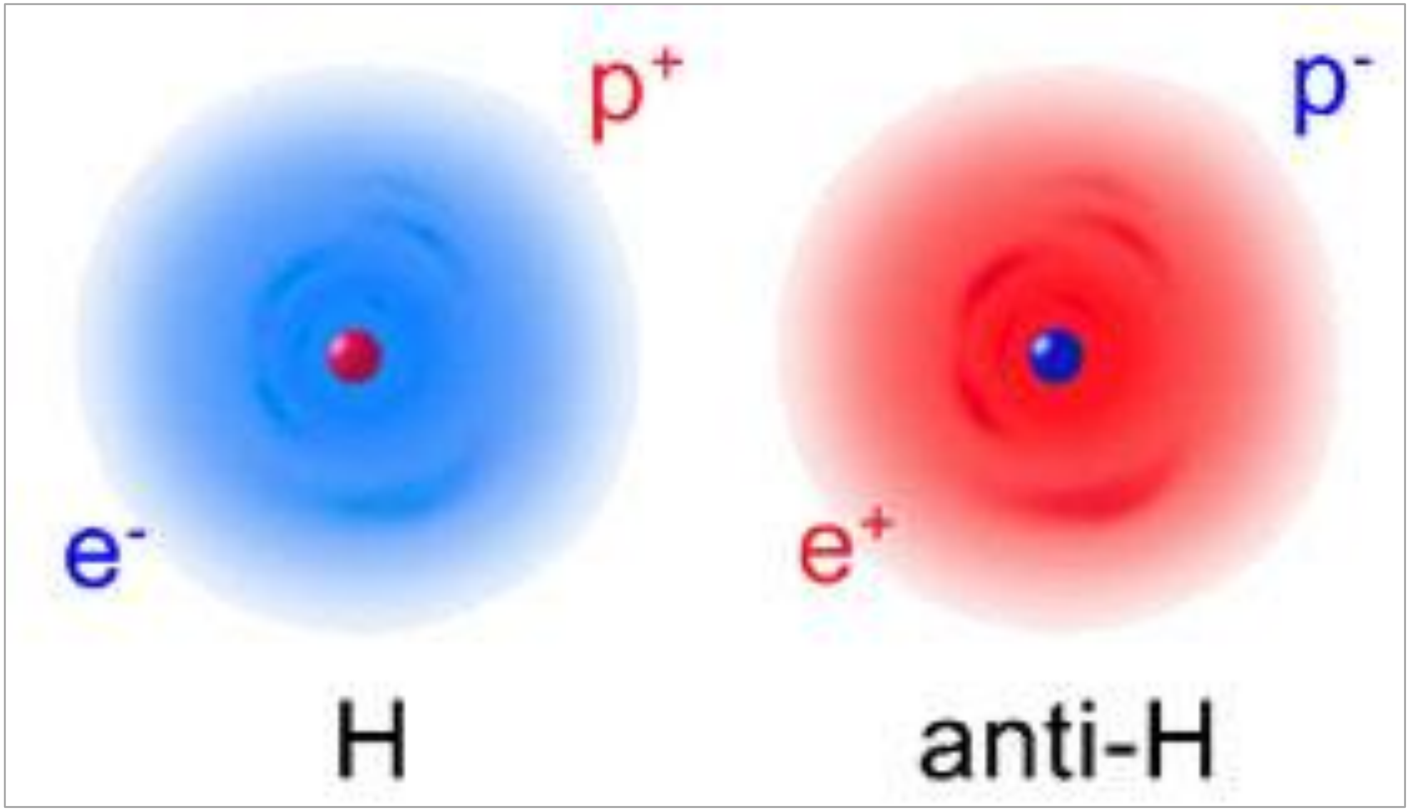







Discovery of **antiparticles** (P.A.M. Dirac, 1928, C.D. Anderson, 1932)

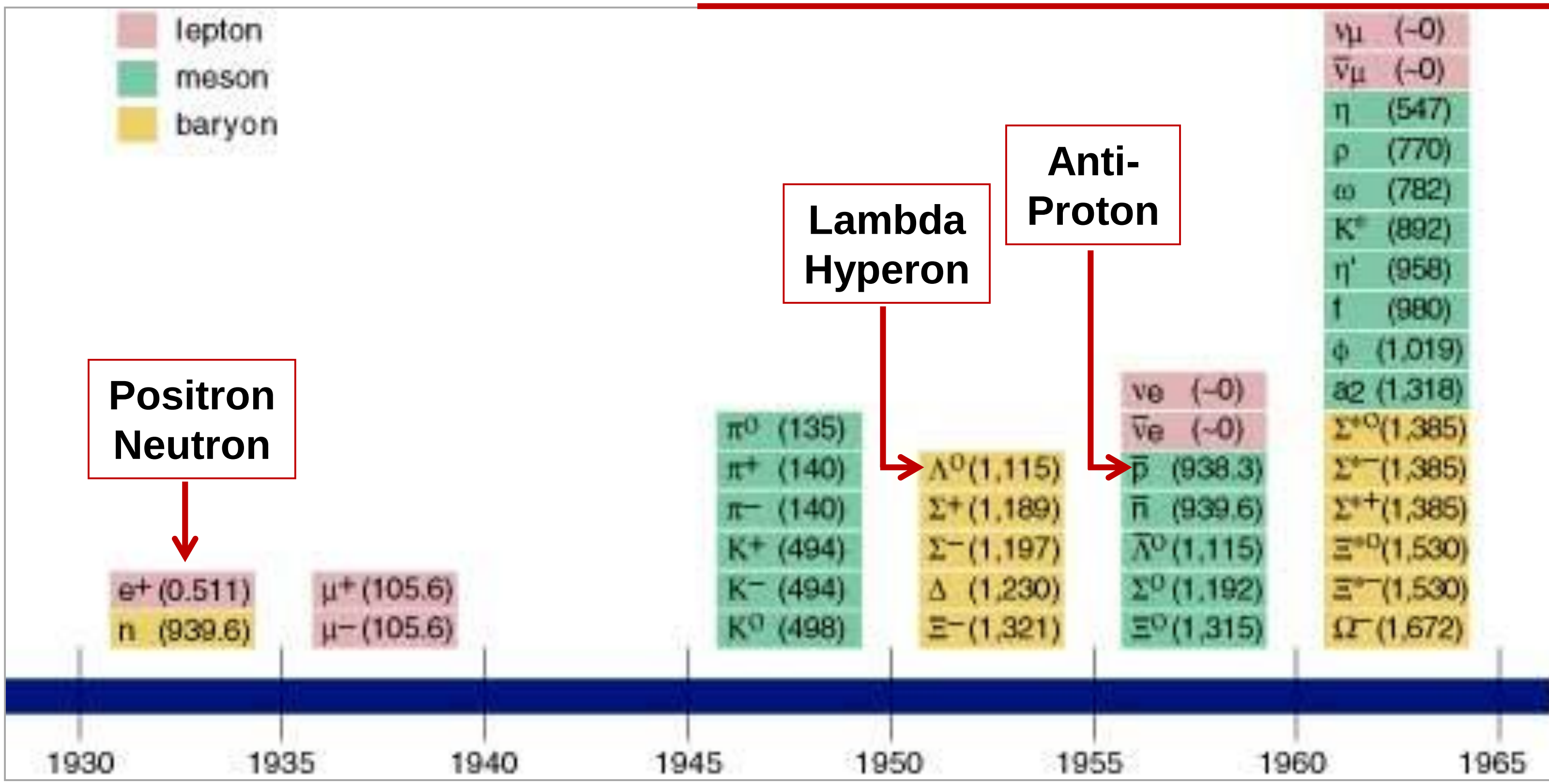
Introduction – History



Duplication: **matter** and **anti-matter**

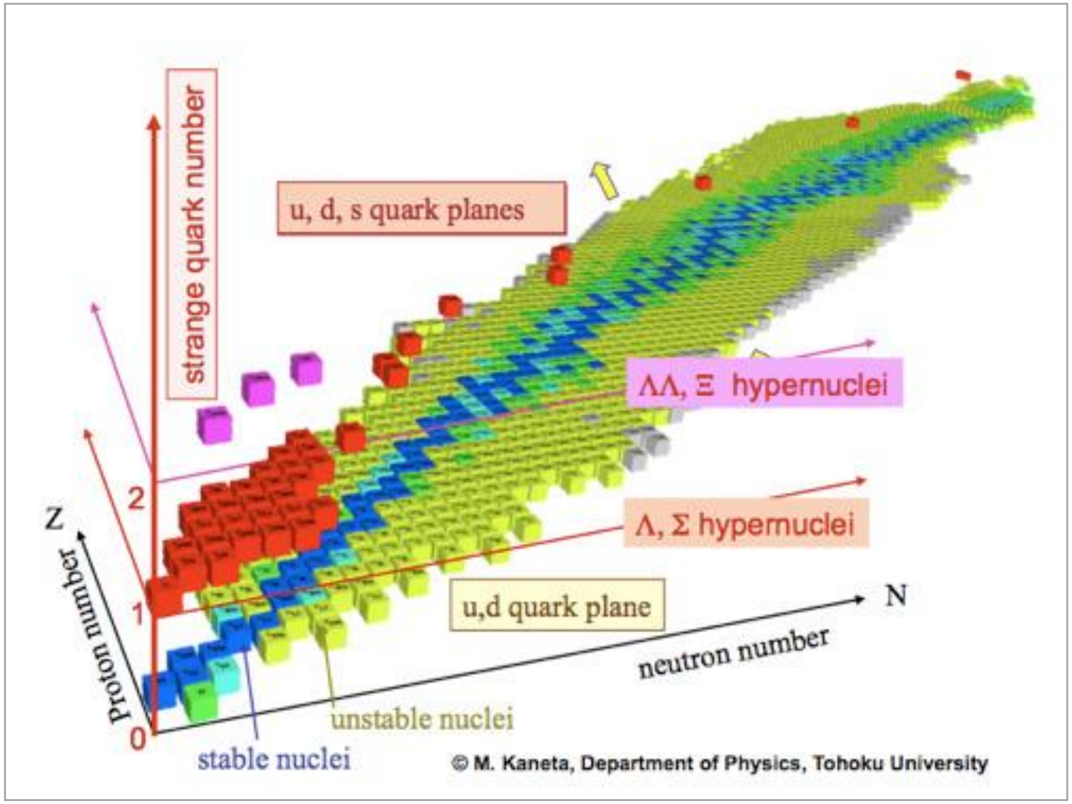
Introduction – History

The era of accelerators …



Observation of a „zoo“ of sub-atomic particles and anti-particles

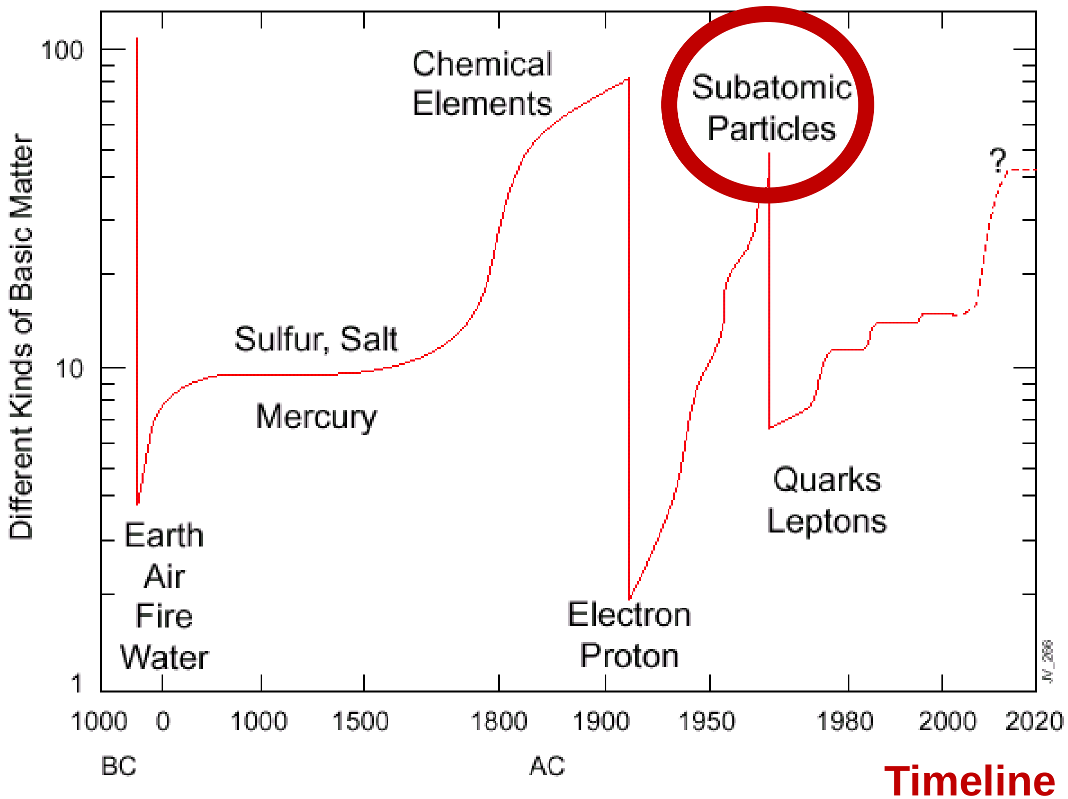
Introduction – History



"Hypernuclei"

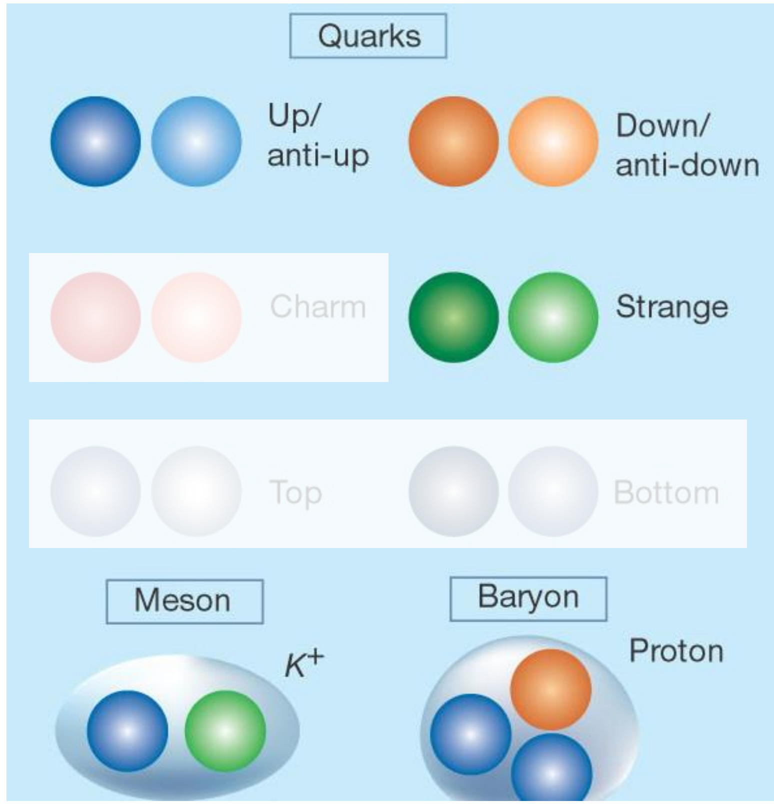
The extended „Table of Isotopes"

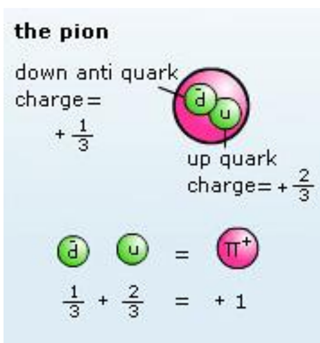
Introduction – History

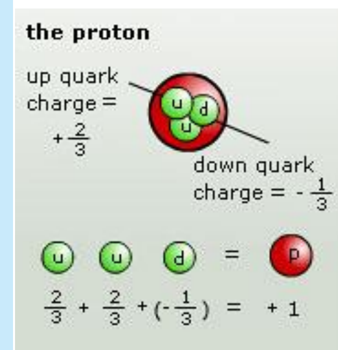


The up´s and down´s in the number of matter constituents

Introduction – **History**

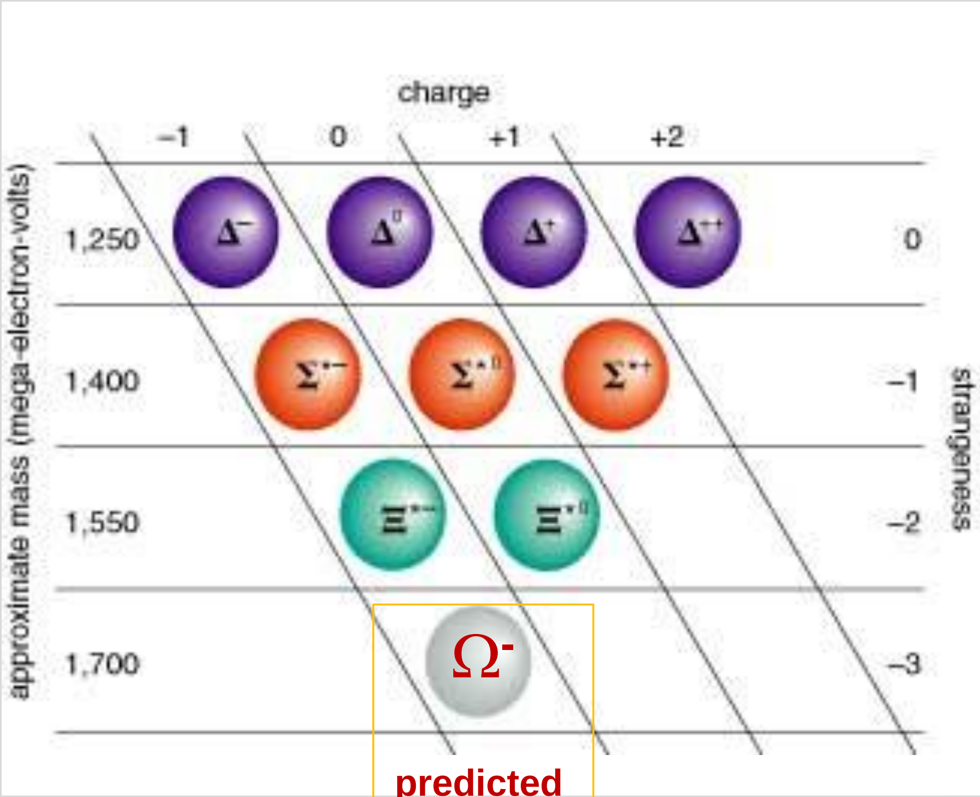




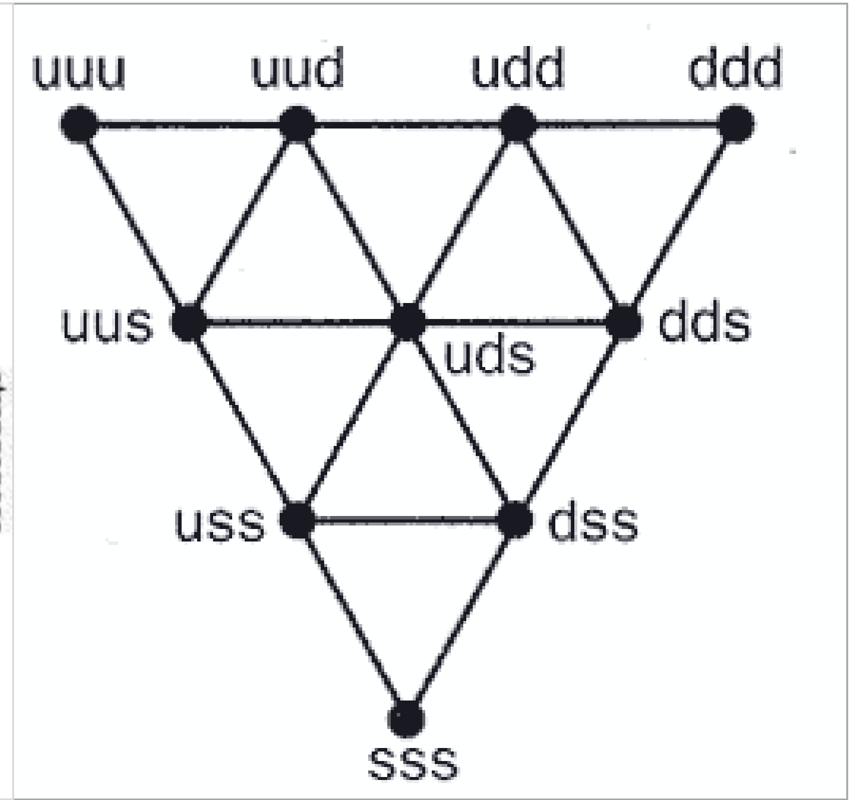


M. Gell-Mann and G. Zweig (1964): **Quarks** („Aces“)

Introduction – History

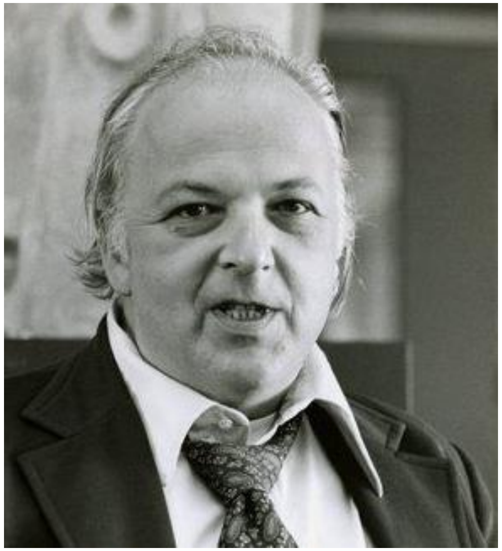


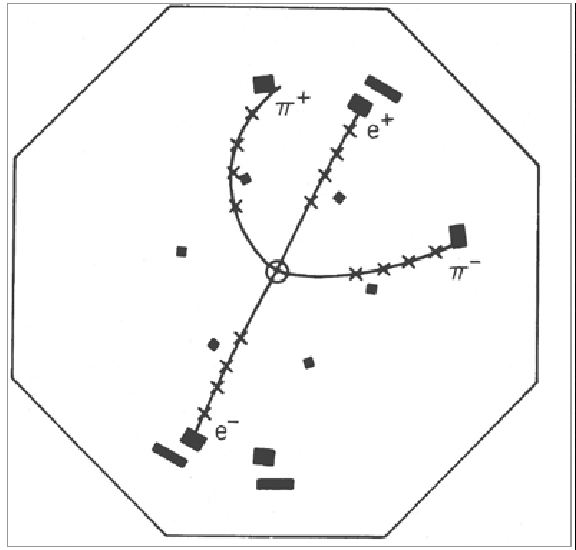
predicted
and found

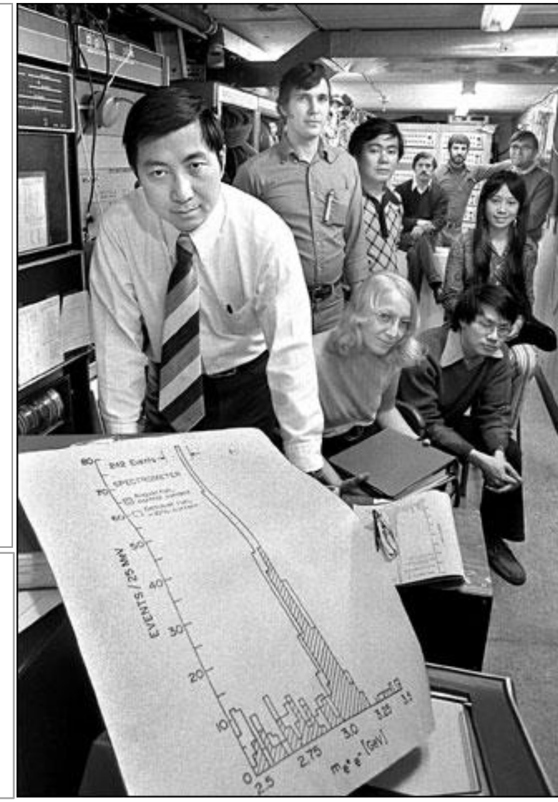


Hadrons (baryons & mesons) appear in „multiplets“: all members found

Introduction – History







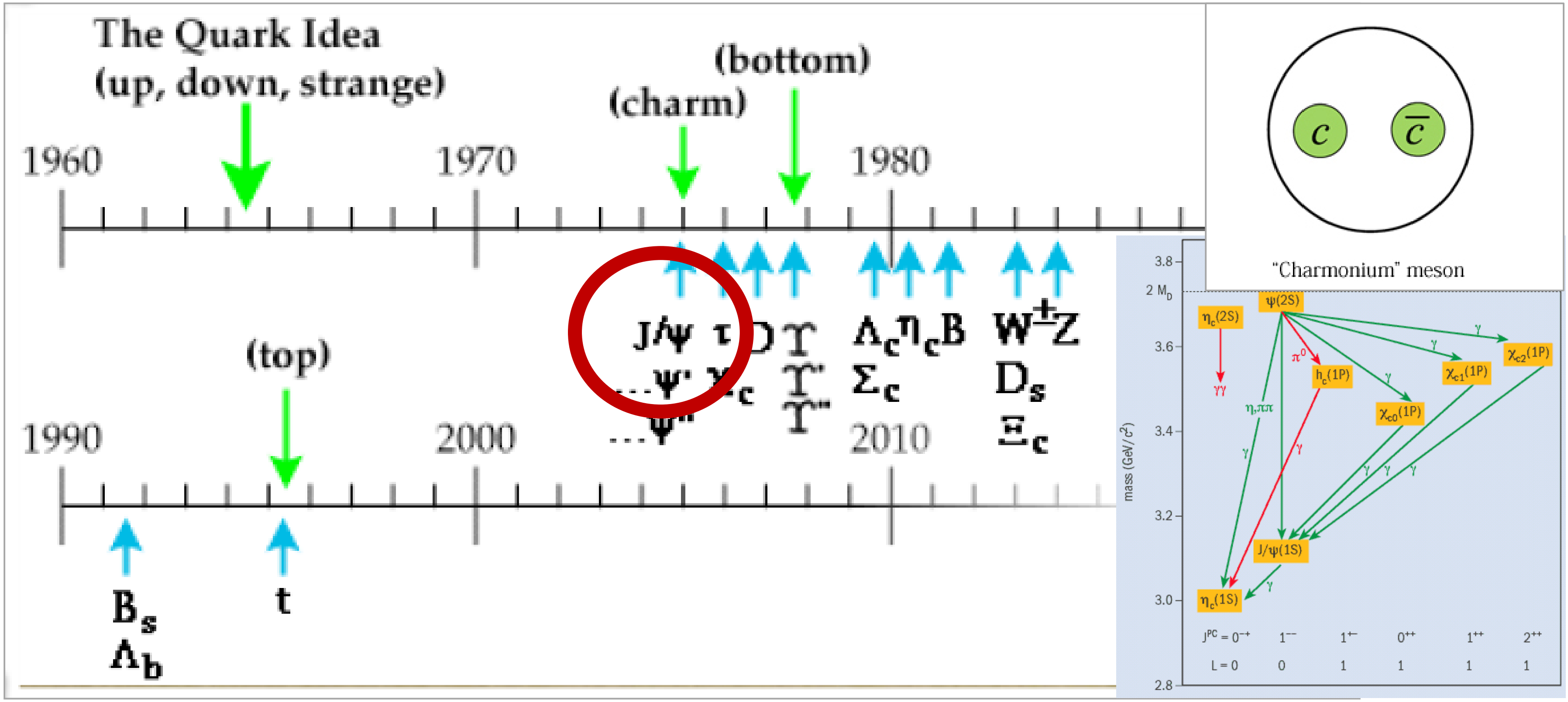
$J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3096.916±0.011 OUR AVERAGE				

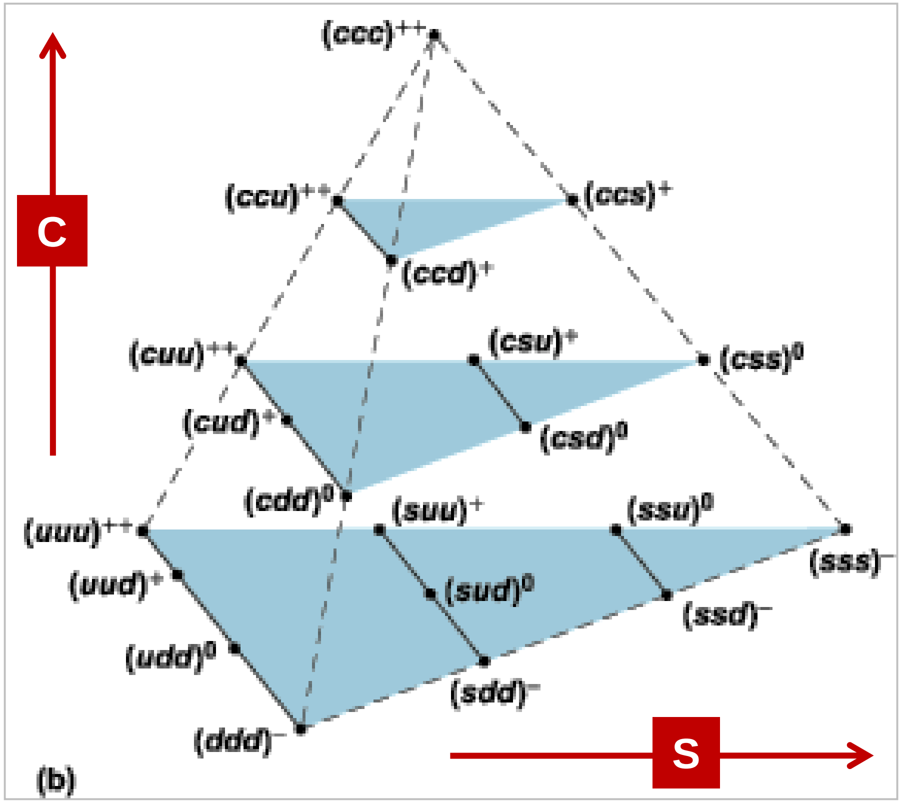
B. Richter and S. Ting (1974): **J/Psi** (charm-quark)

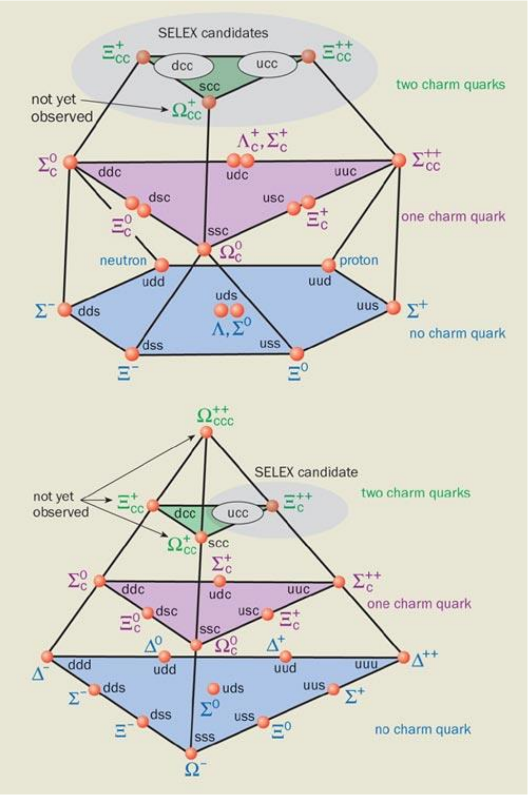
Introduction – History



Charm quark → „**Charmonium**“

Introduction – History





3-dimensional **multiplets** (u,d.s.c, …)

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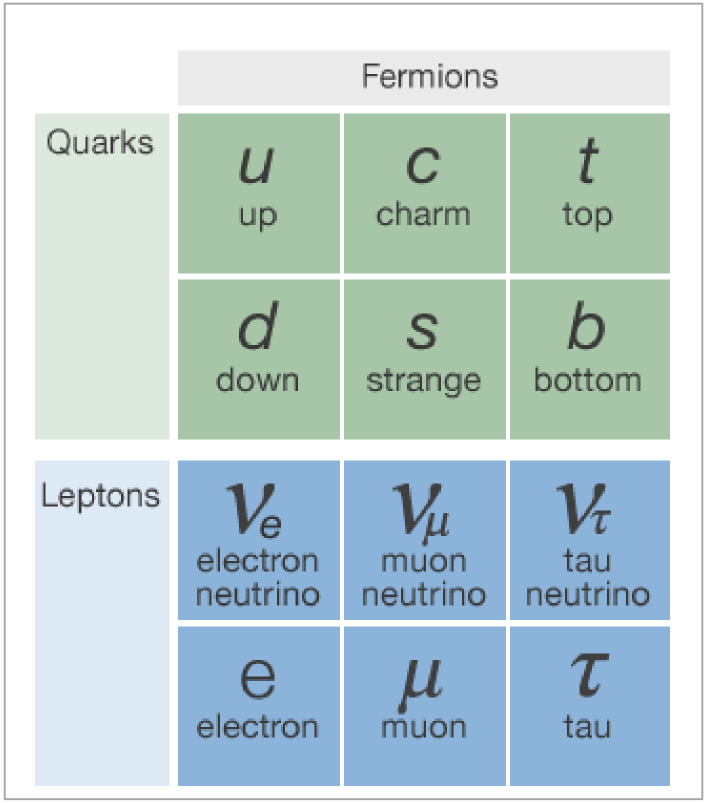


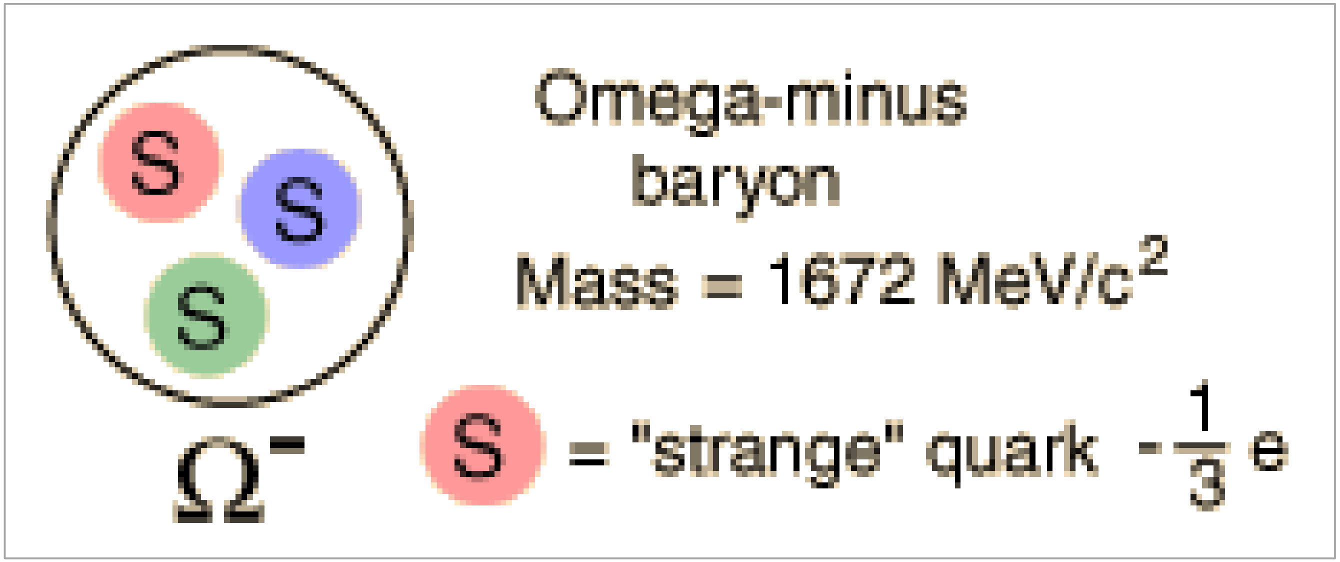
Why are there 3 "families" of particles?

Can there be more at higher mass?

Free leptons but no free quarks - why?

Matter particles (plus: antiparticles)

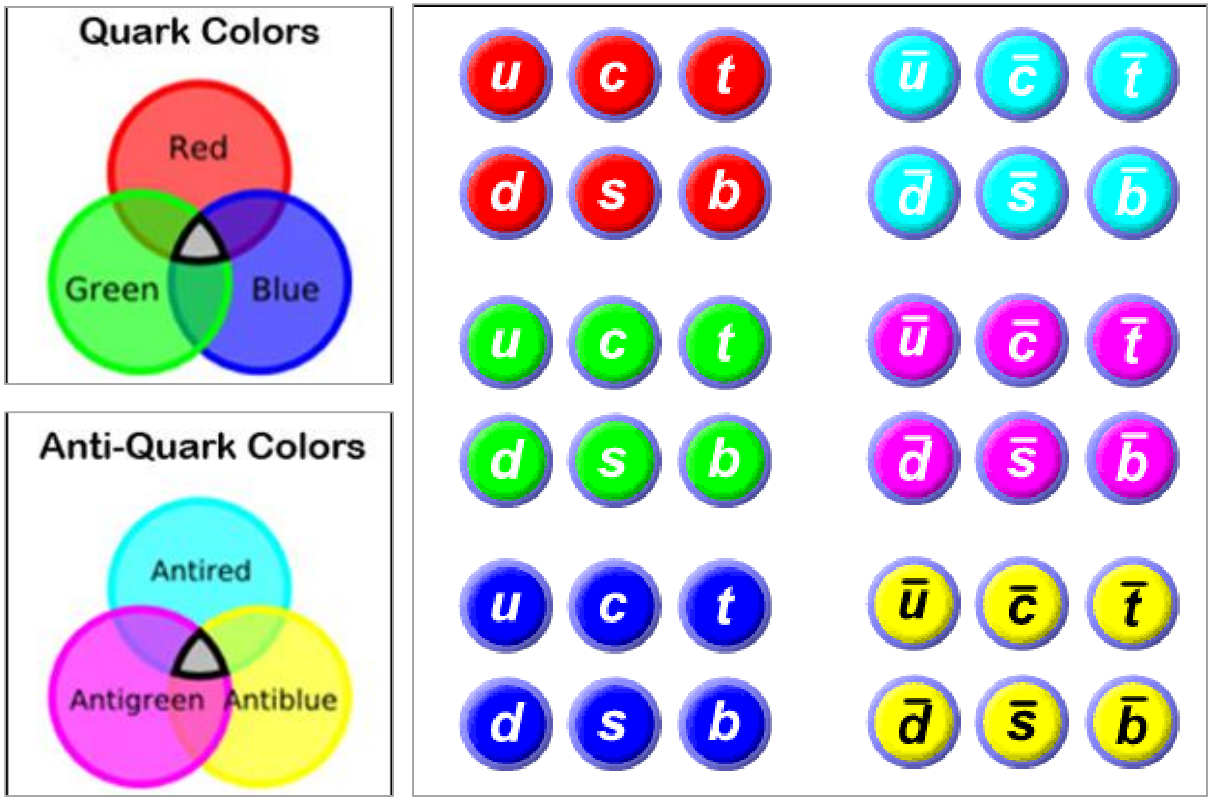
Introduction – History



Baryons with 3 identical quarks (uuu, ddd, sss, …)
in the ground-state violate the *Pauli-principle*
→ need for a new tag to distinguish them: "color"

Quarks have **„color"** as a new quantum number

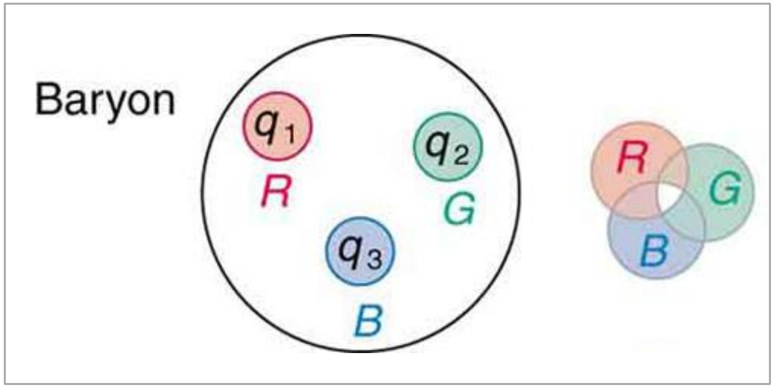
Introduction – History

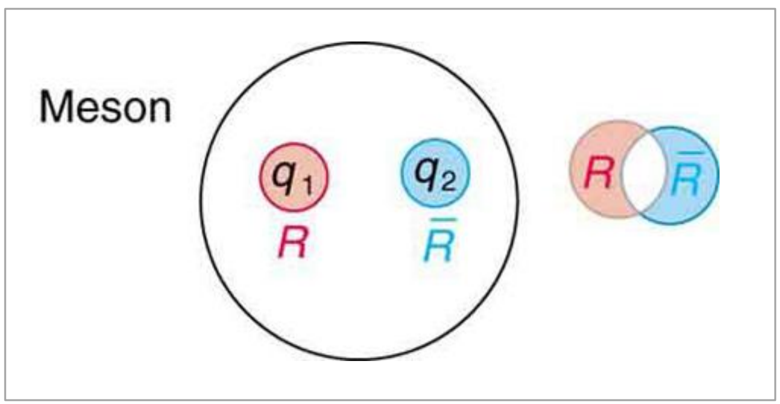


Quarks carry color, anti-quarks anti-color

Quarks have **„color“** as a new quantum number

Introduction – History

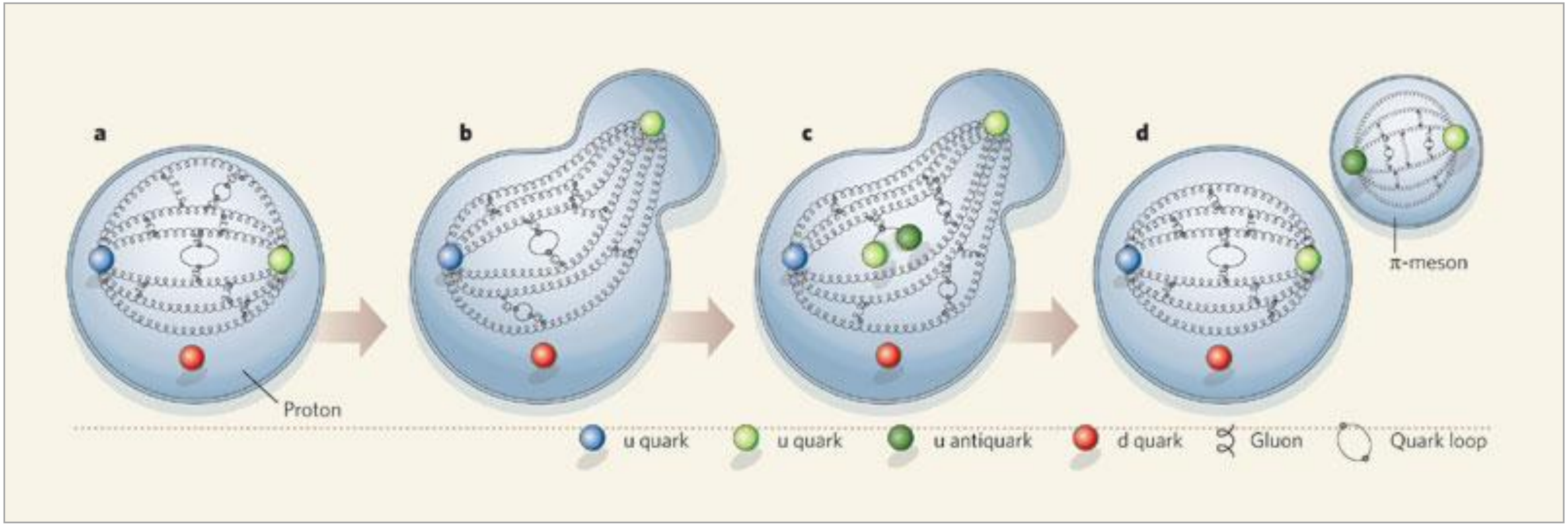




Bound states (hadrons) are color-neutral ("white")

No free quarks: „confinement"

Introduction – History



Trying to isolate a quark (e.g. by excitation) leads to no free quark but a meson

No free quarks: „confinement“

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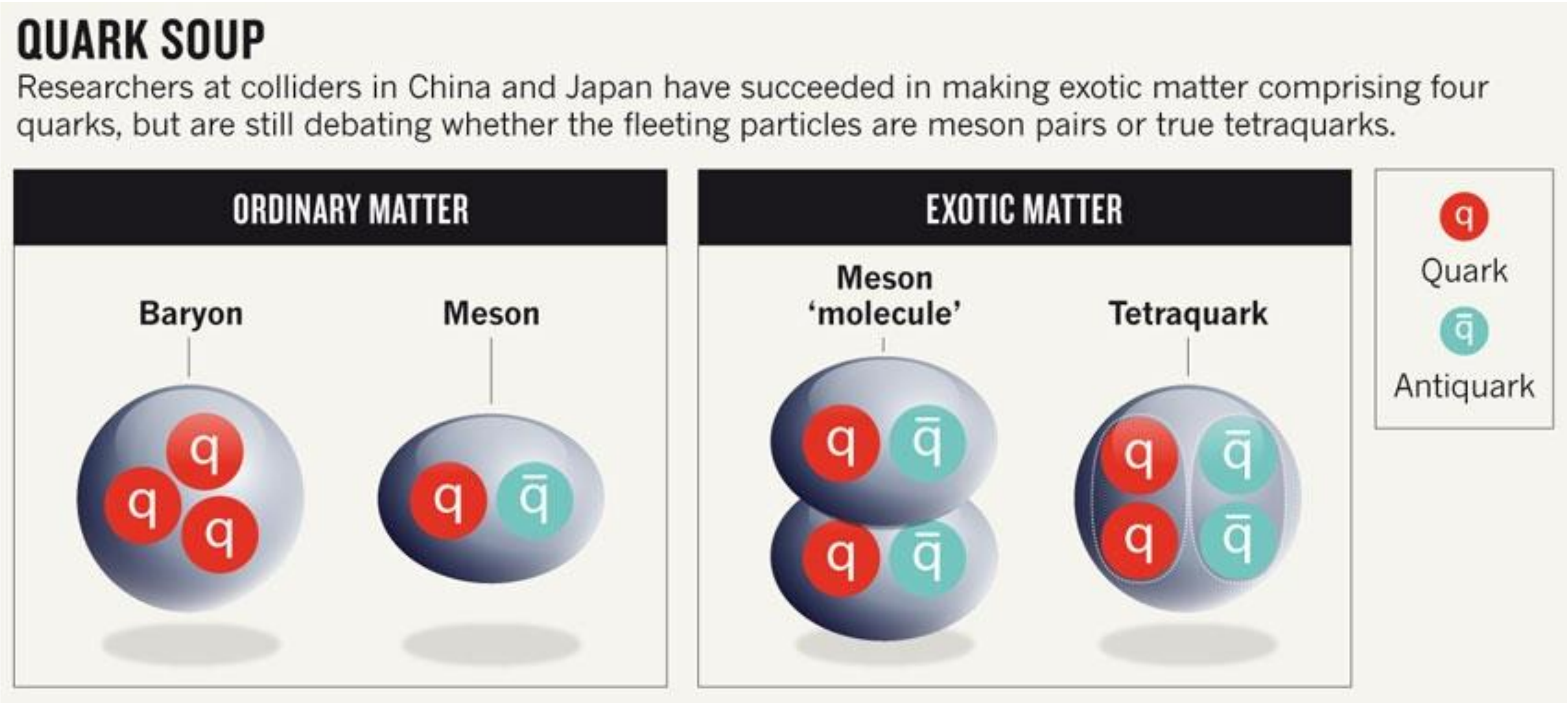
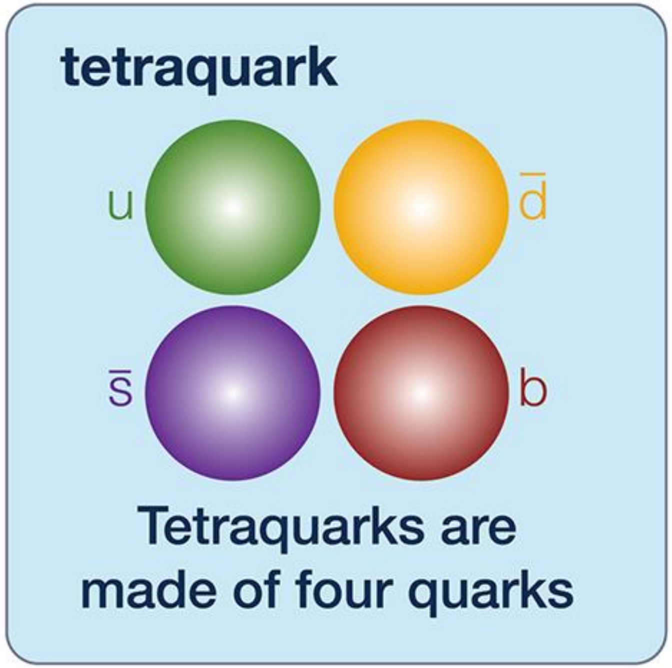


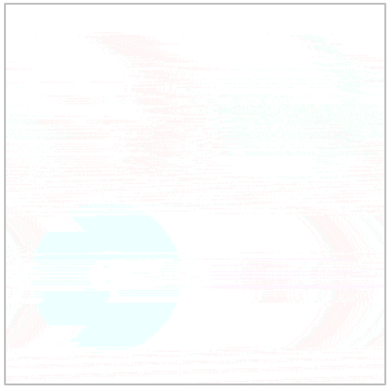
Bound states (hadrons) are color-neutral ("white")

Which **hadrons** exist in Nature?

Introduction – History



This is X(5568), which is made of an up, down, strange and bottom quark.



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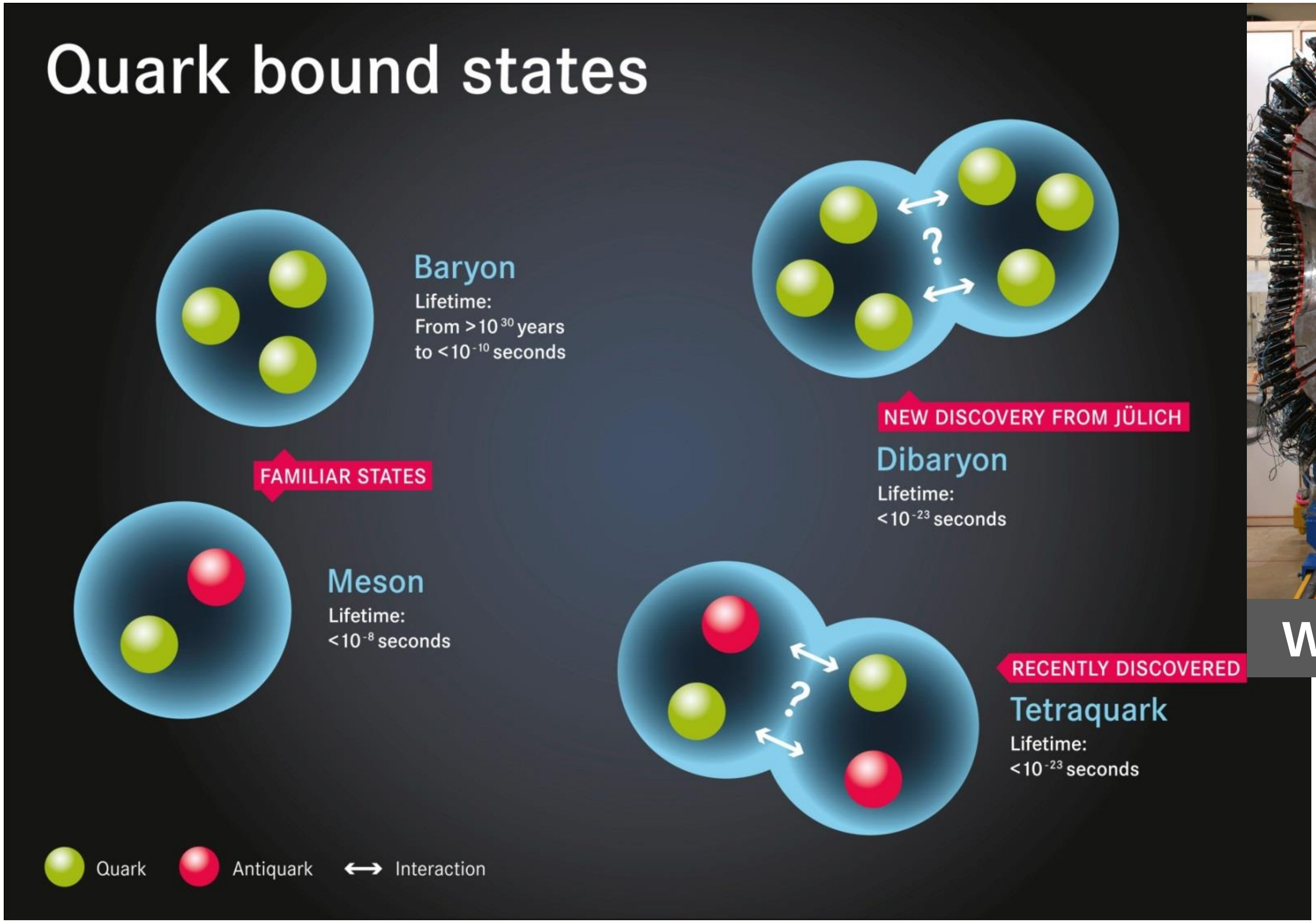
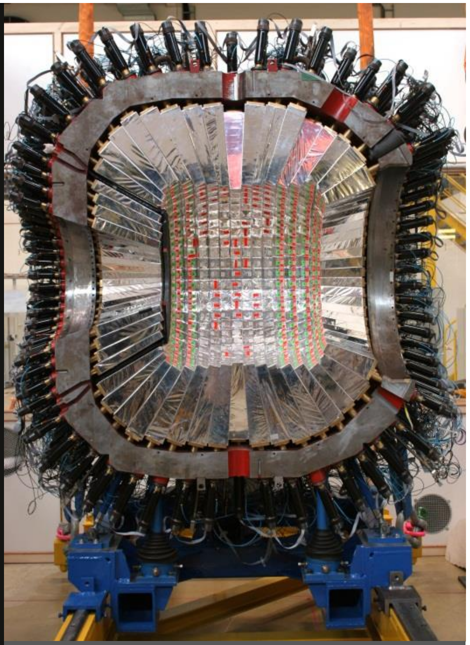
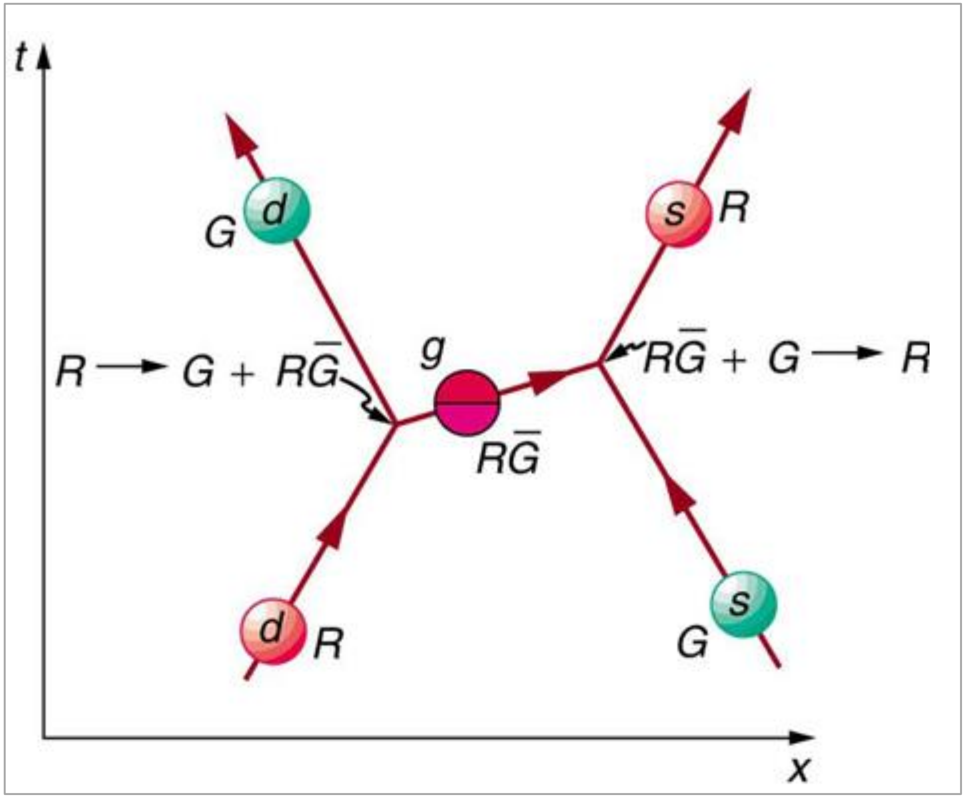




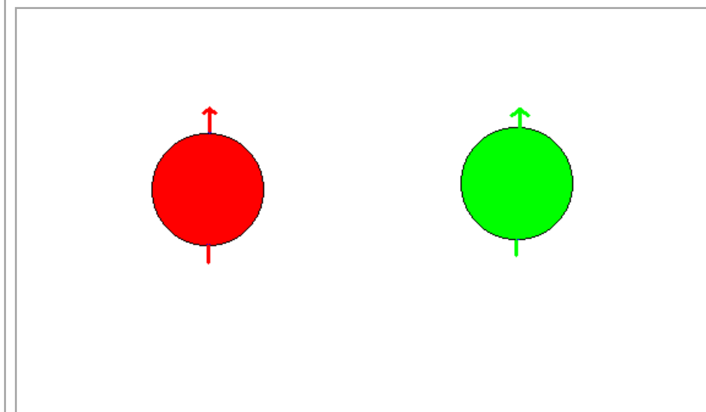
WASA at COSY

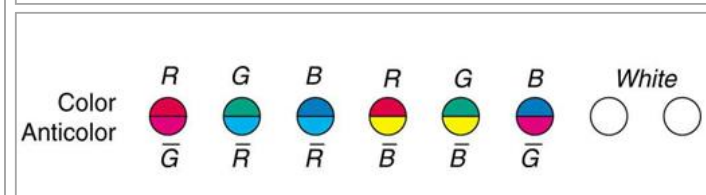
Which **hadrons** exist in Nature?

Introduction – History



Gluons carry color anti-color

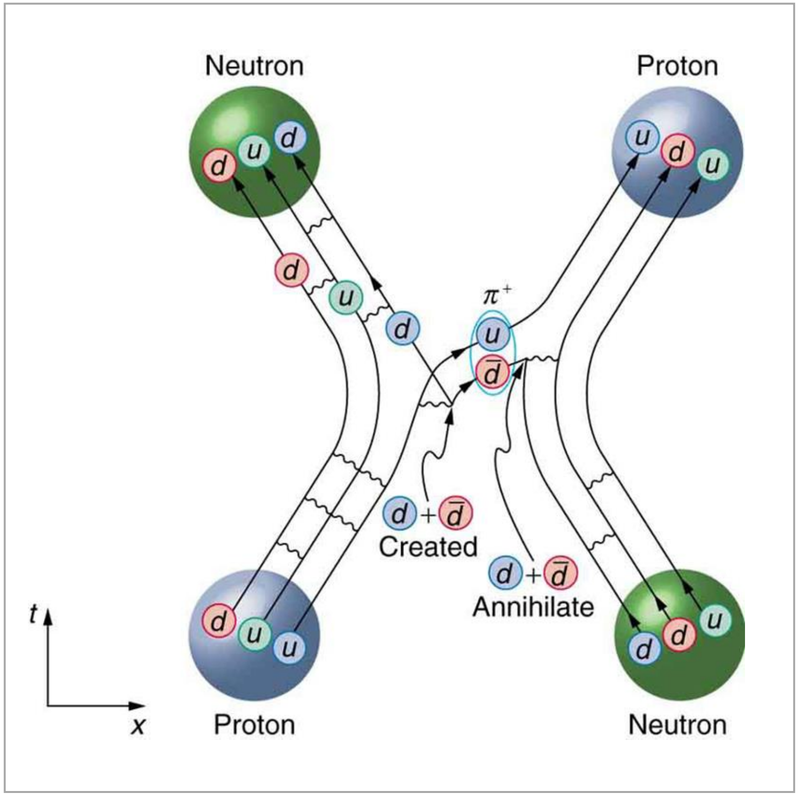




Interaction between quarks

Strong interaction is mediated by **gluon exchange**

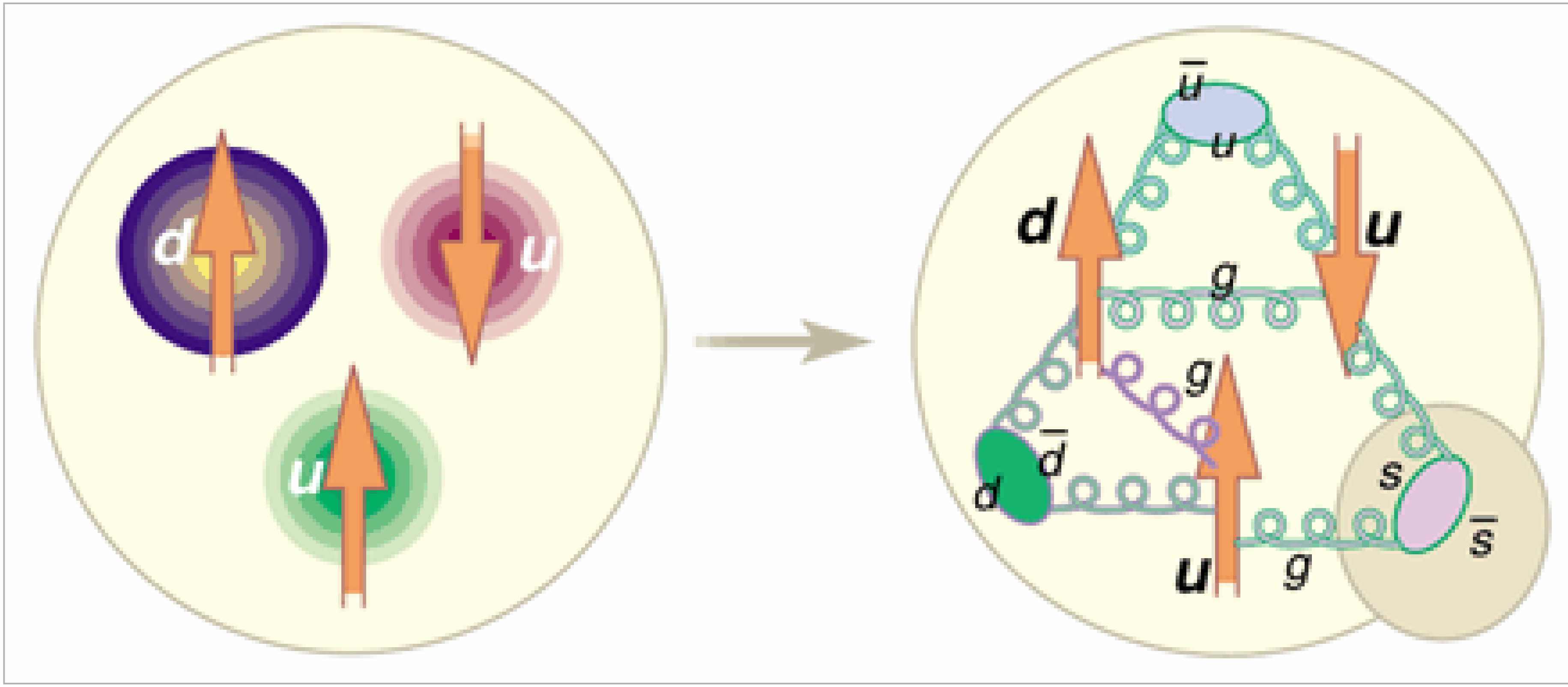
Introduction – History



Interaction between hadrons

Nuclear interaction is mediated by **meson (e.g. pion) exchange**

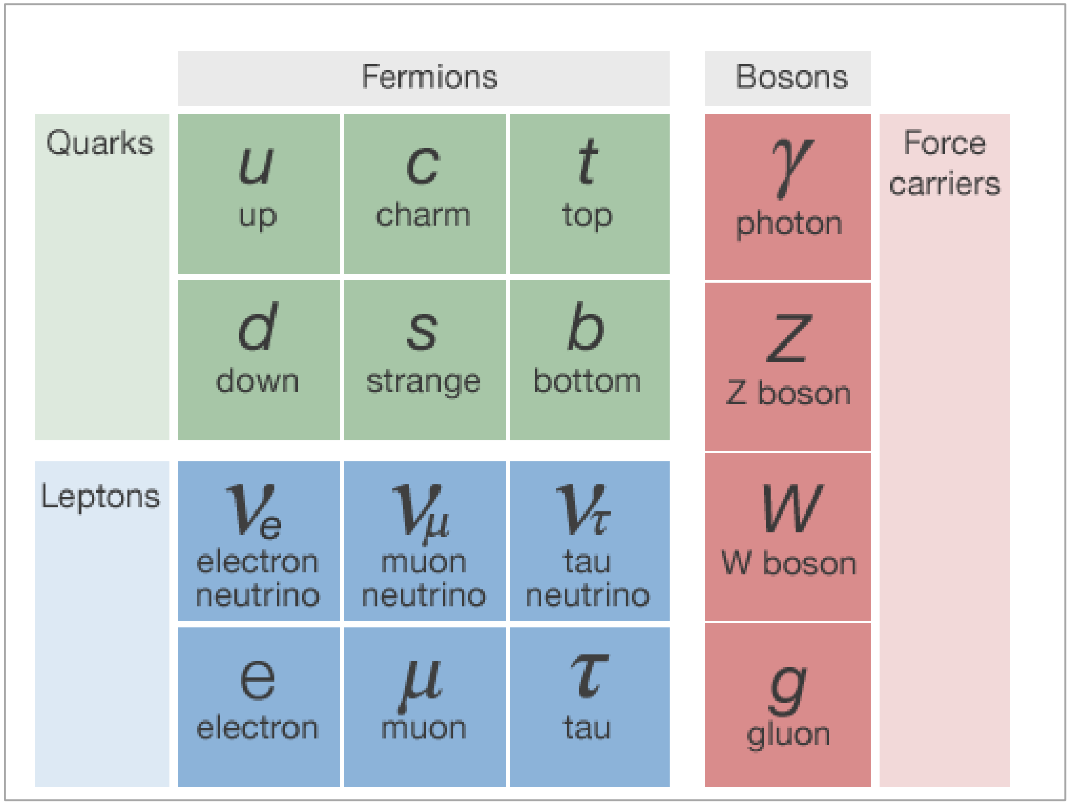
Introduction – History

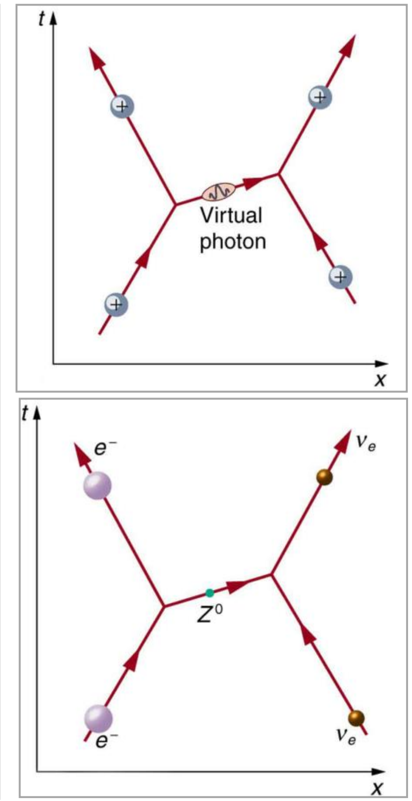


“Constituent quarks” and “sea quarks”

Hadrons (e.g. nucleons) are complex systems

Introduction – History





Interaction between quarks

Force particles (exchange bosons)

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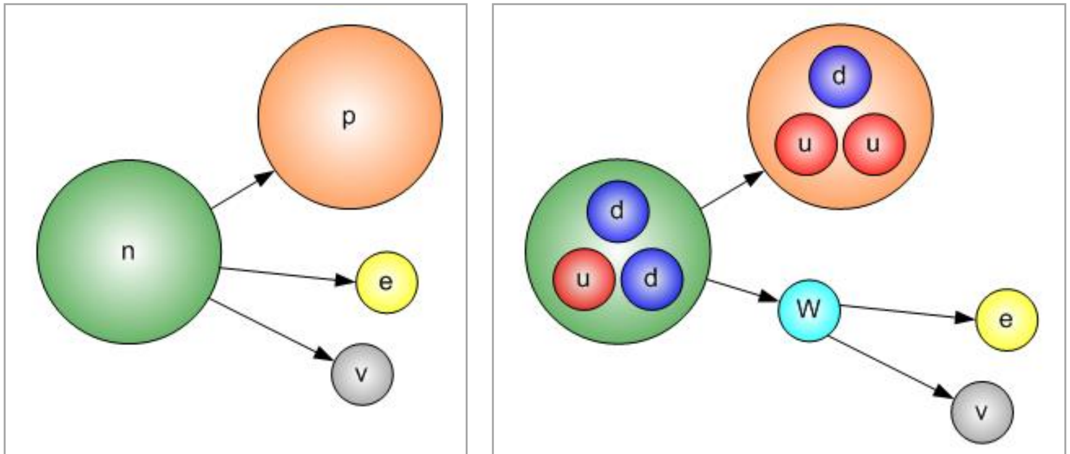
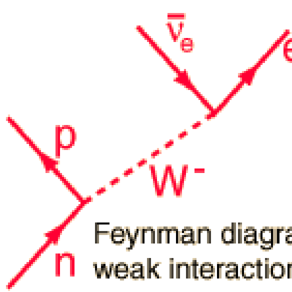


Weak force only interaction capable of **changing** one **type of quark** into another

W^+ W^- 80.4 GeV

Z^0 91.2 GeV



Feynman diagram for weak interaction involved in beta decay.

3 gauge bosons for “**charged**” and “**neutral currents**”

Weak interaction

Weak interaction acts between all fermions

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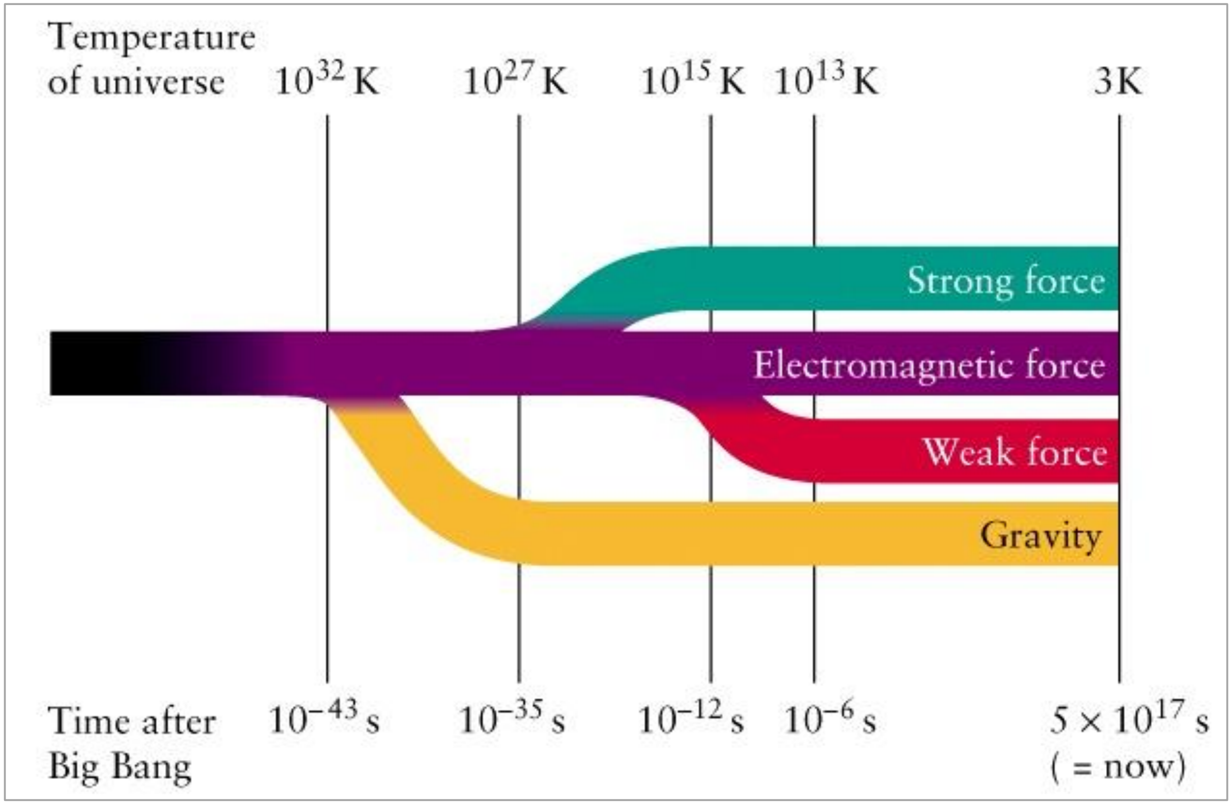
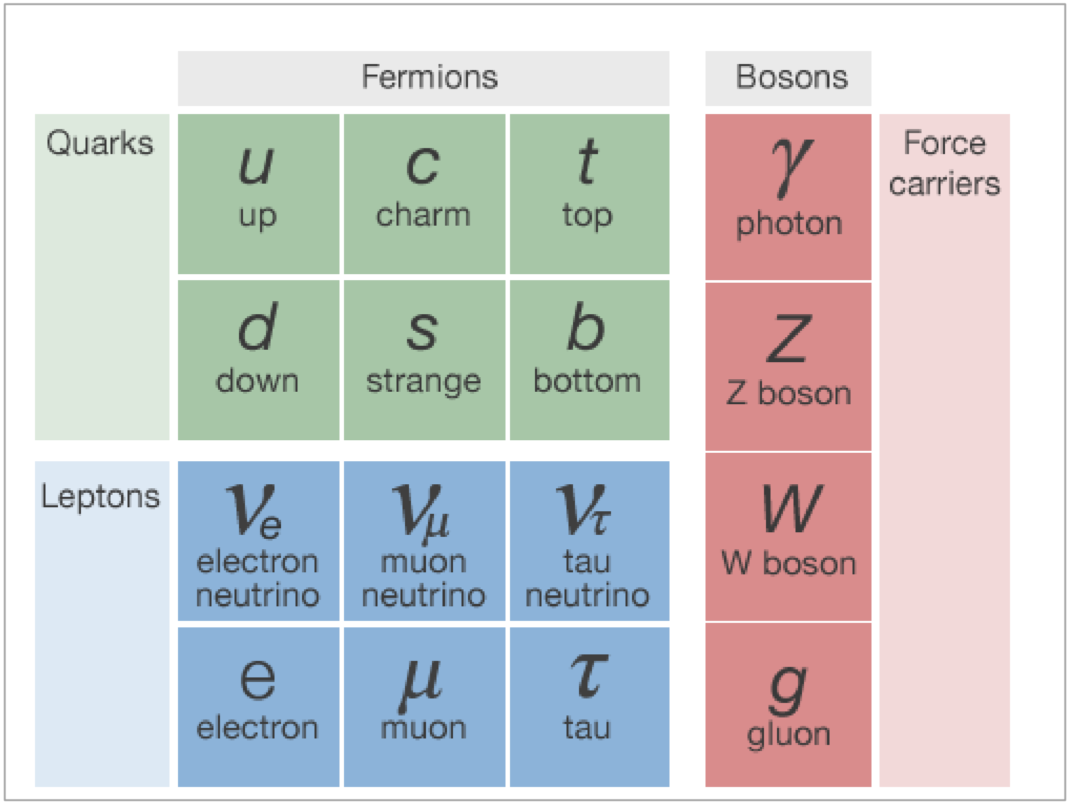


Unification of forces

Fundamental interactions

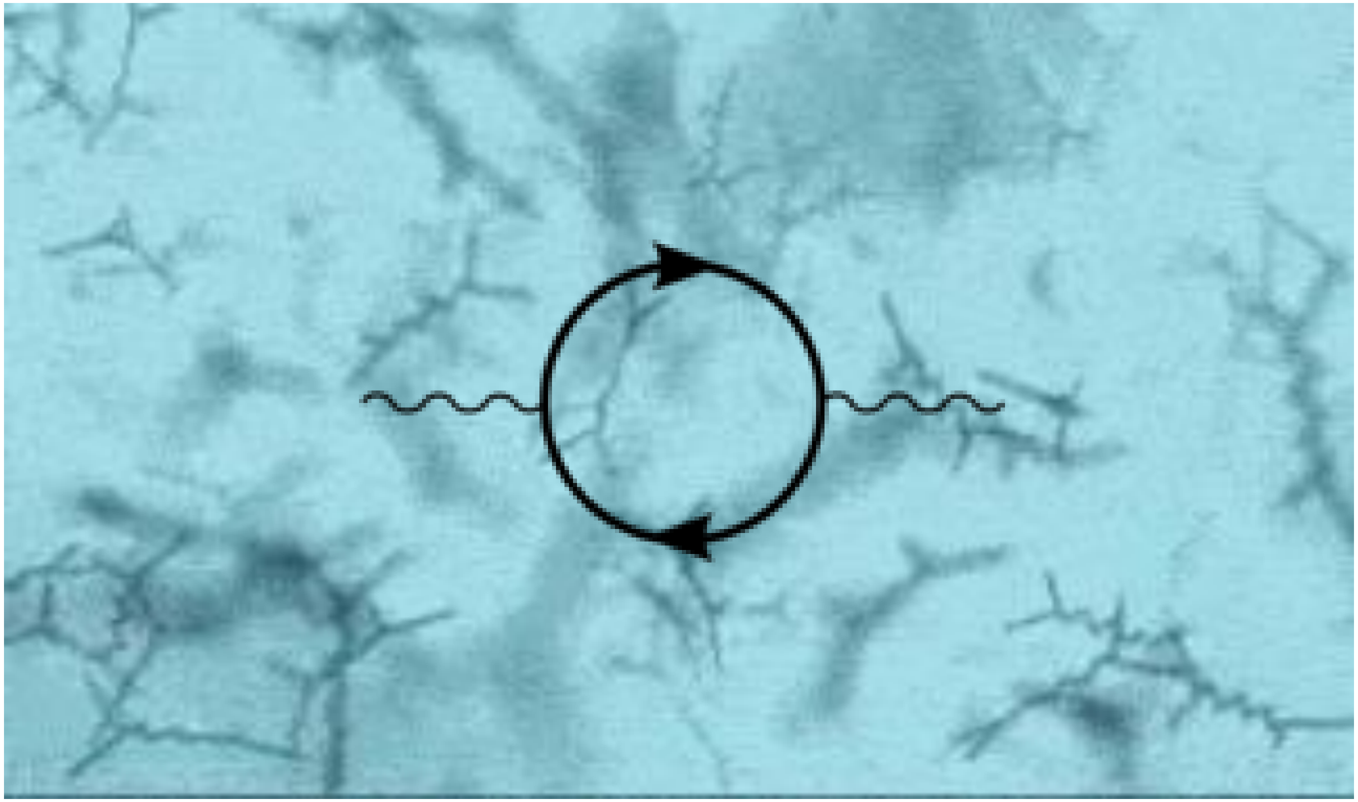
Introduction – History



What gives these particles (different) mass?

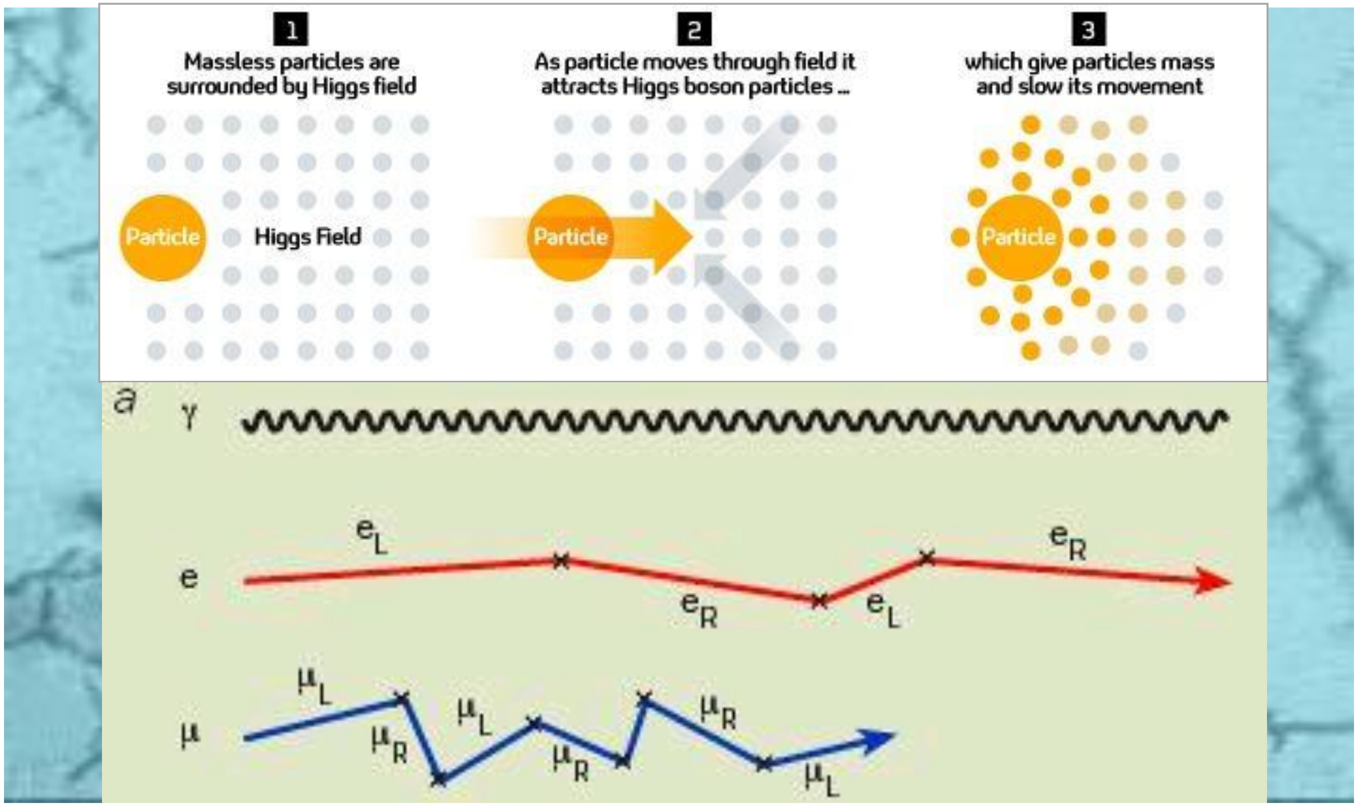
Internal consistency of Standard Model: **Higgs meachanism**

Introduction – Current Status



Countless Higgs-Bosons („Higgs-field“) permeate all of the space

Introduction – Current Status



Countless Higgs-Bosons („Higgs-field“) permeate all of the space

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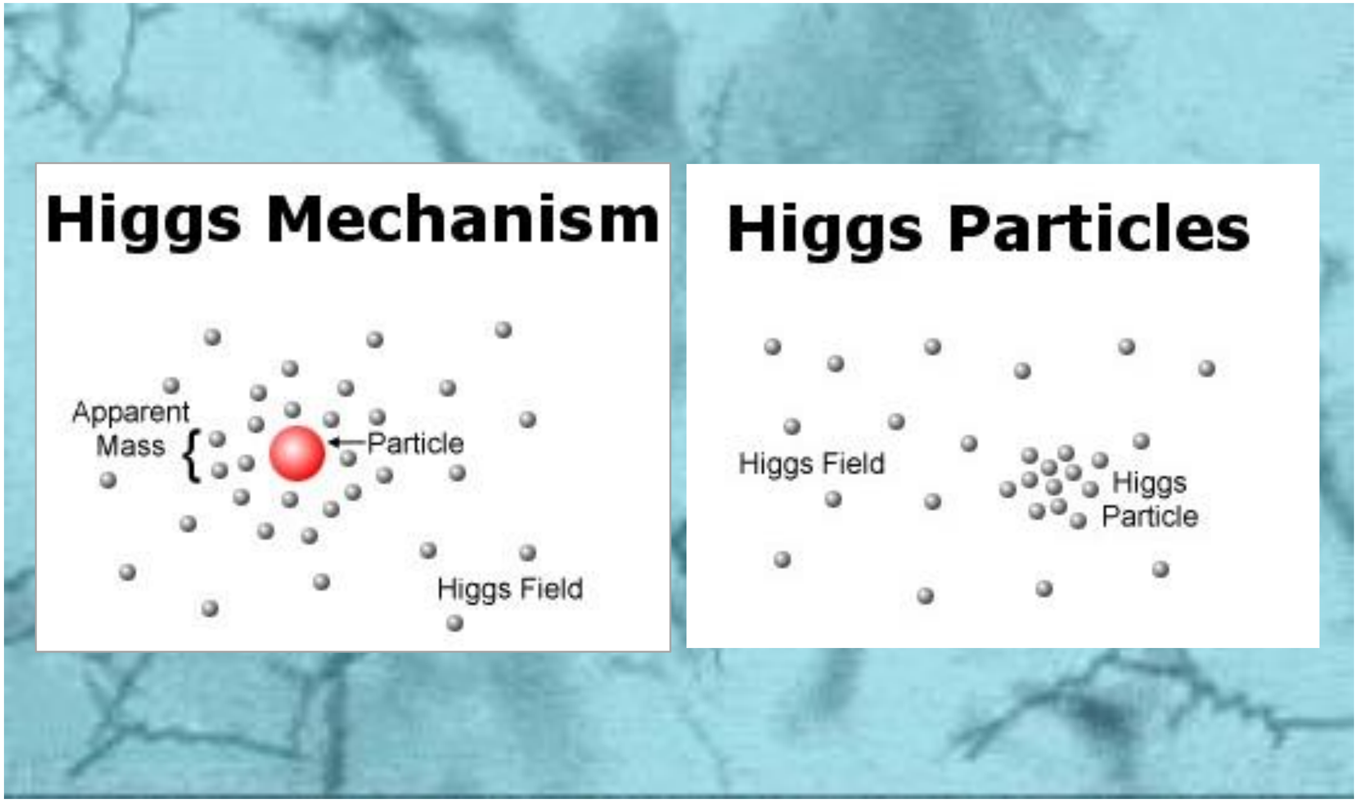
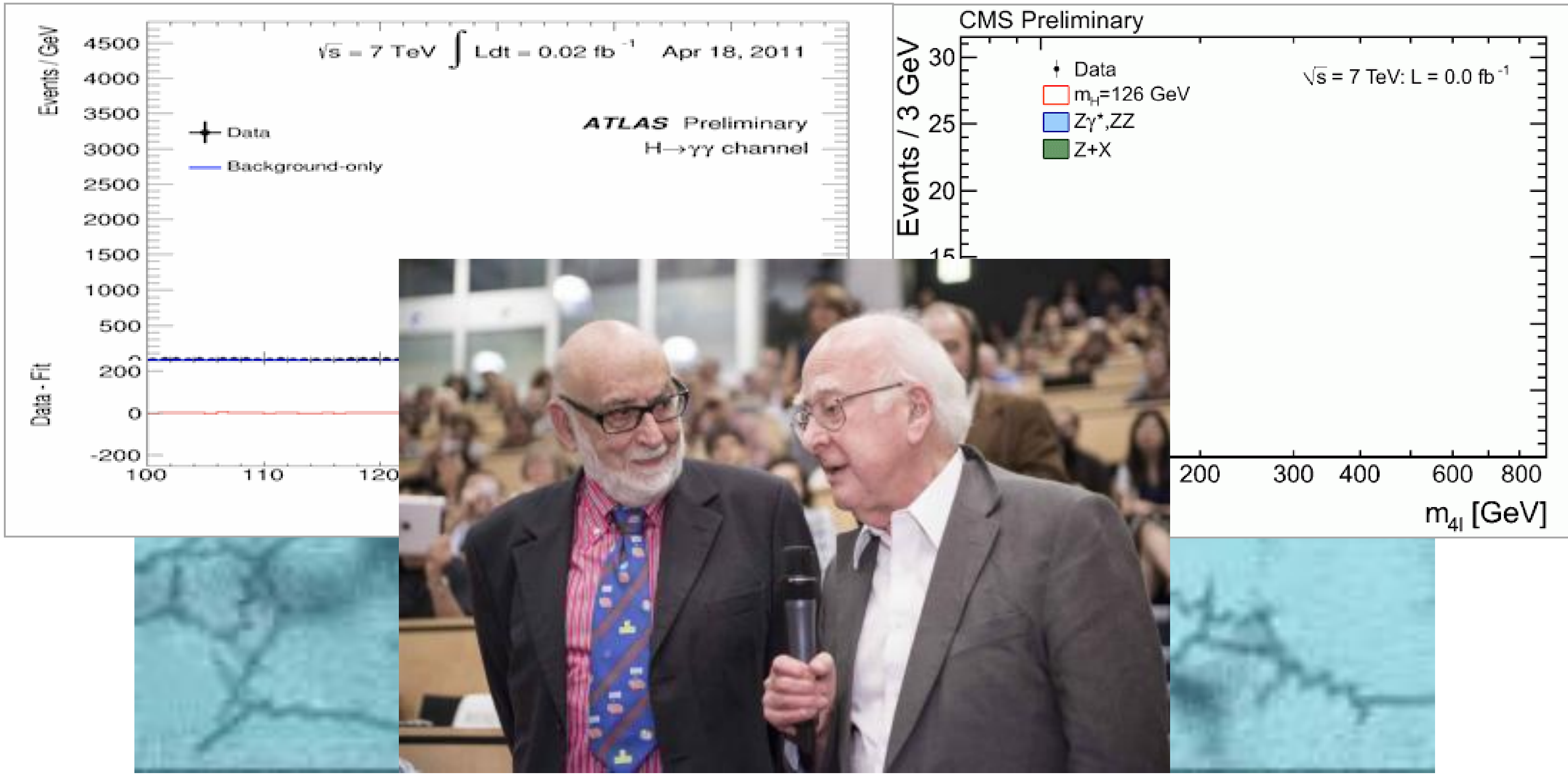


Higgs boson

Countless Higgs-Bosons („Higgs-field“) permeate all of the space

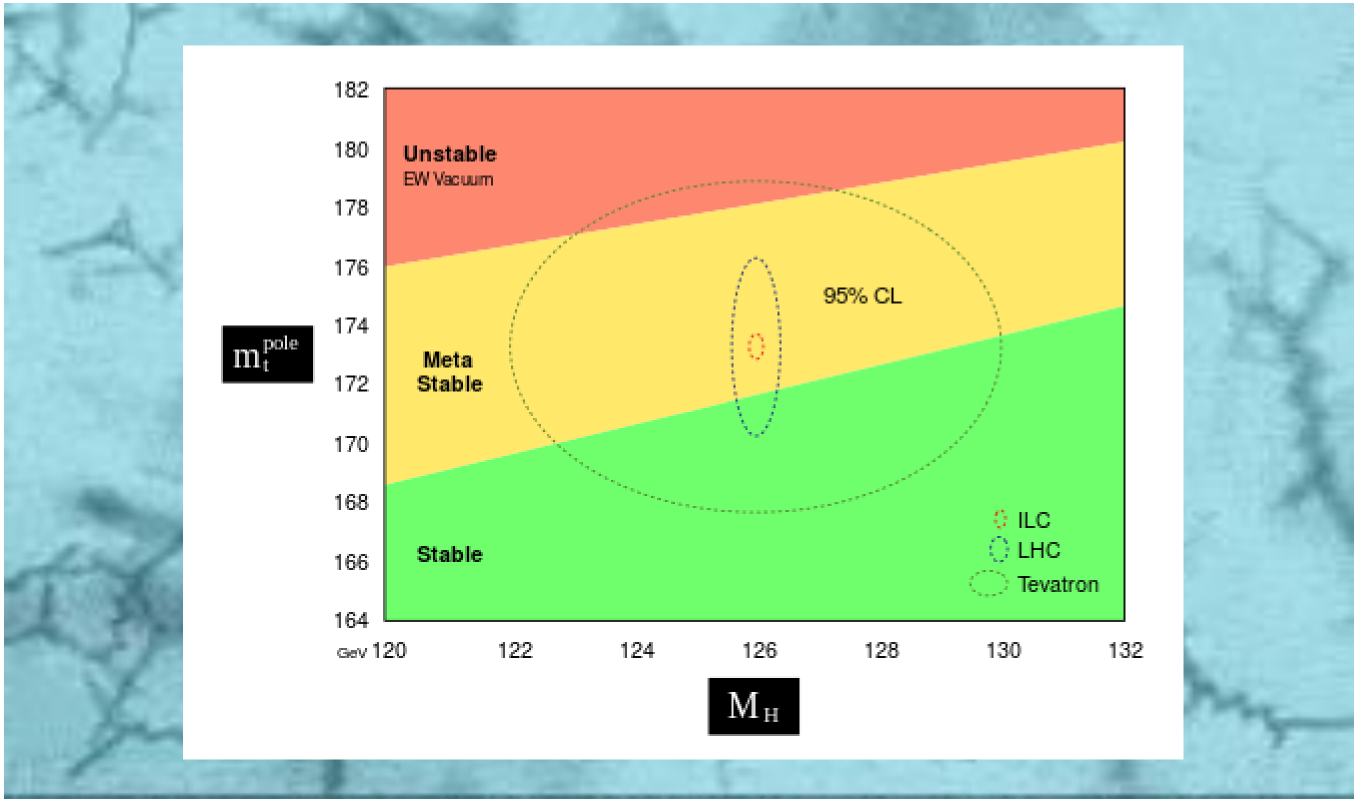
Introduction – Current Status



Higgs boson

Countless Higgs-Bosons („Higgs-field“) permeate all of the space

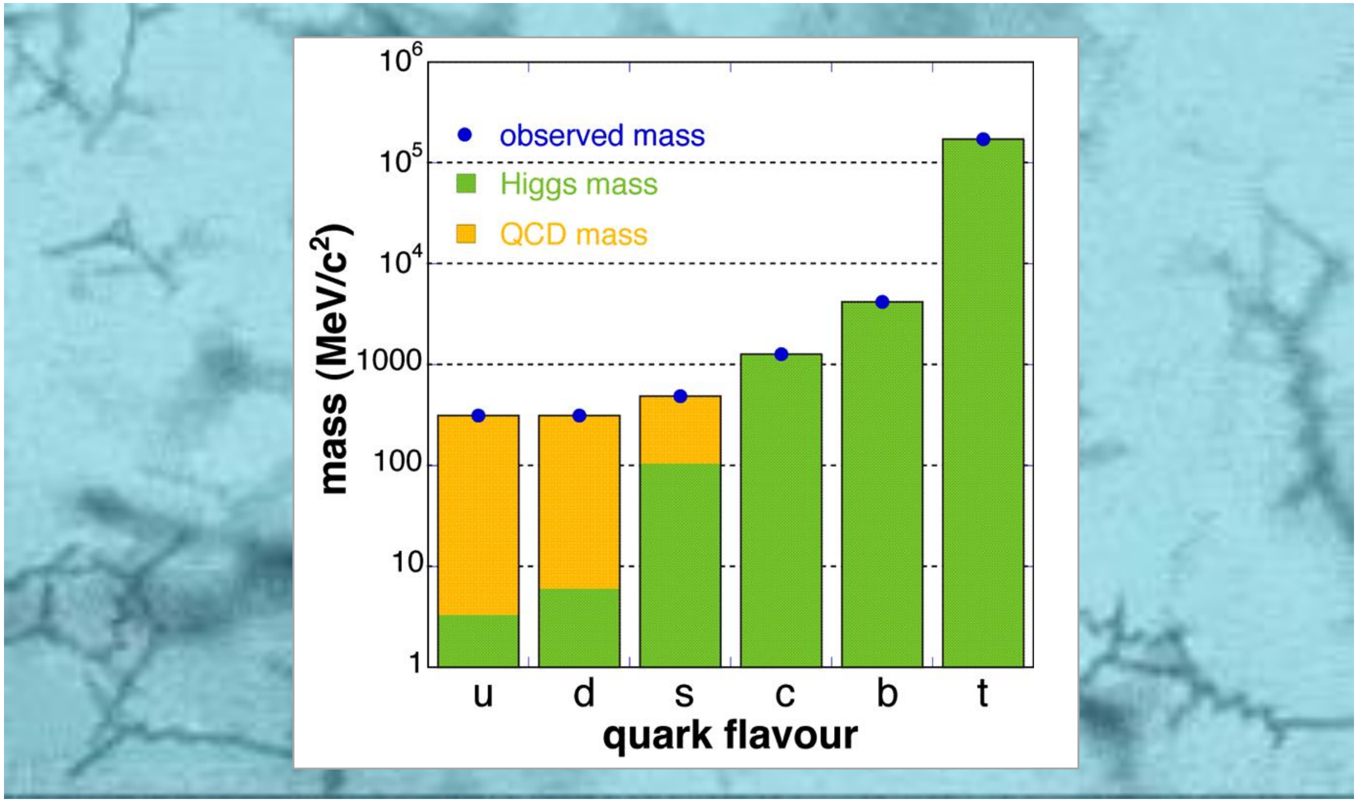
Introduction – Current Status



Higgs boson

Countless Higgs-Bosons („Higgs-field“) permeate all of the space

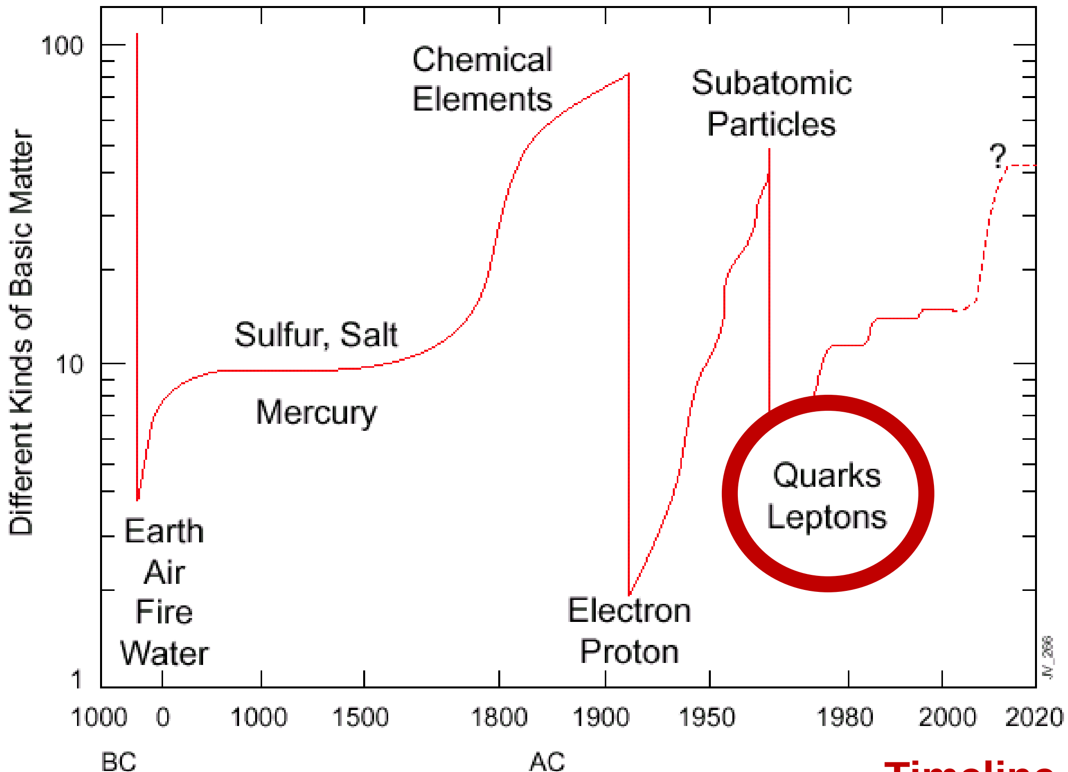
Introduction – Current Status



Higgs mechanism contributes little to mass of nucleons

Countless Higgs-Bosons („Higgs-field“) permeate all of the space

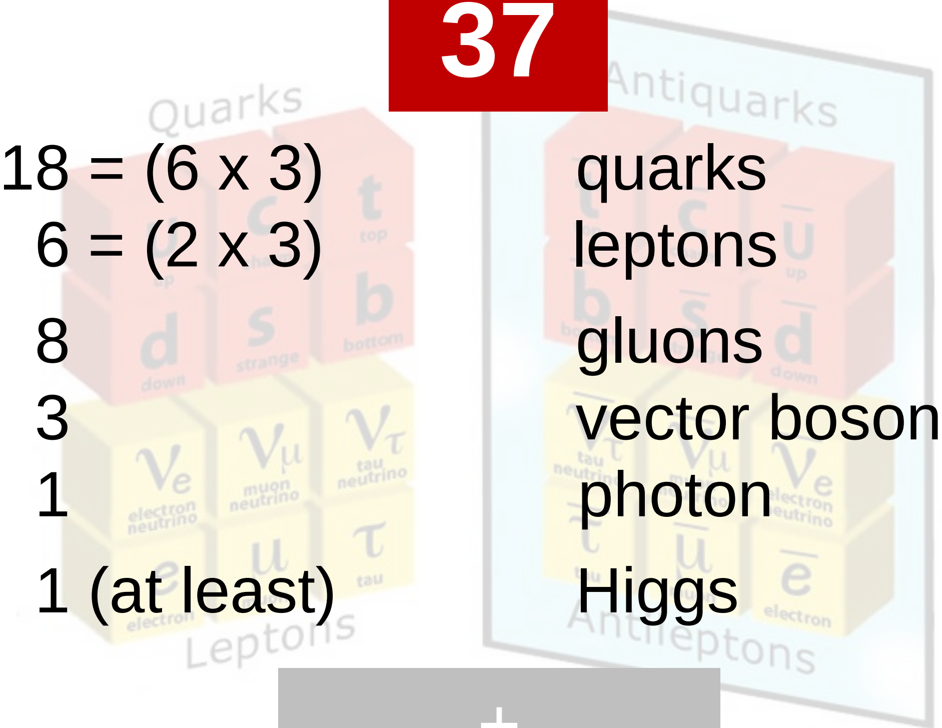
Introduction – Current Status



Timeline

The up´s and down´s in the number of matter constituents

Introduction – Current Status



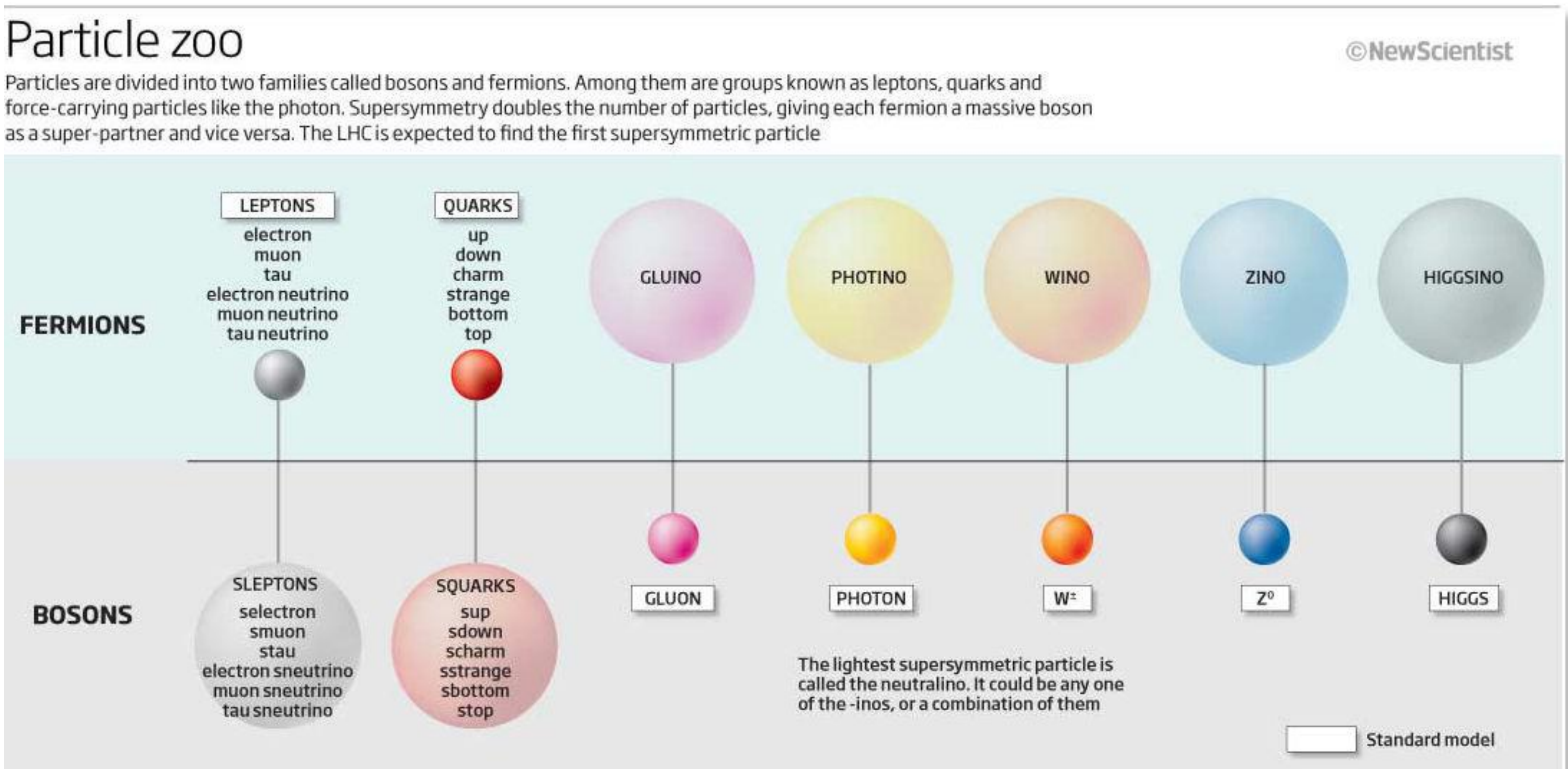
37

18 = (6 x 3)	quarks
6 = (2 x 3)	leptons
8	gluons
3	vector bosons
1	photon
1 (at least)	Higgs

+ antiparticles

The number of Standard Model-particles is just too big!

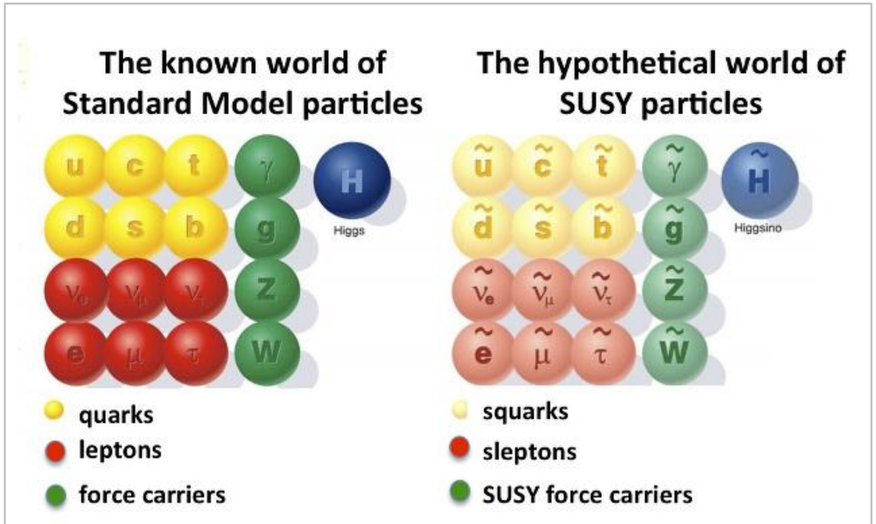
Introduction – Current Status



Supersymmetry (**SUSY**) partners – a **doubling** of particles!

Introduction – Current Status

"Supersymmetry solves problems with the standard model, helps to unify nature's forces and explains the origin of dark matter"

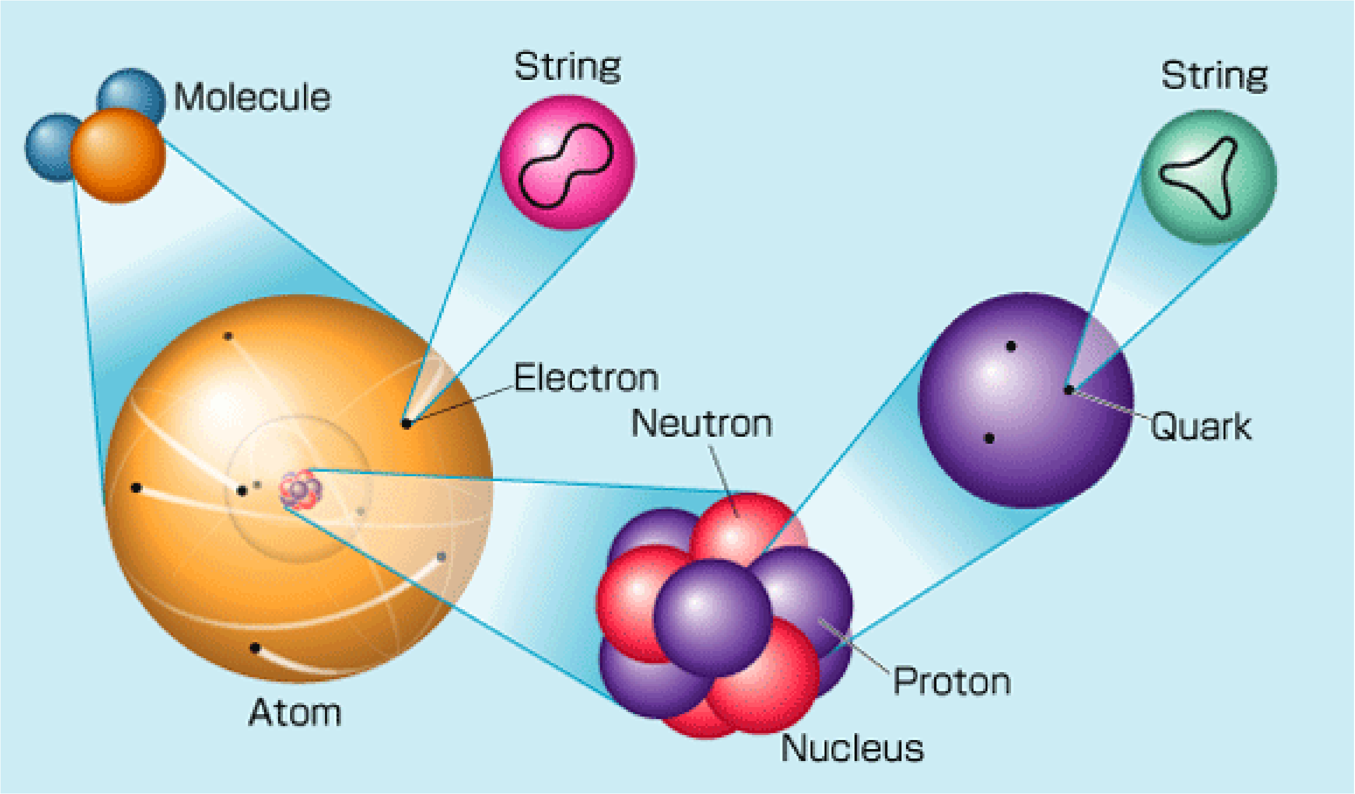


SUSY'S MID-LIFE CRISIS

1970–74	Several theorists independently develop SUSY
1981	Supersymmetric version of the standard model proposed
1983	SUSY used to explain dark matter
1990	SUSY suggested as a way to unify electroweak and strong forces
2000	Large Electron Positron collider (the LHC's predecessor) fails to find evidence of SUSY particles called sleptons
2008	Tevatron sets mass limits on supersymmetric quarks (squarks)
2011	LHC tightens limits on SUSY masses

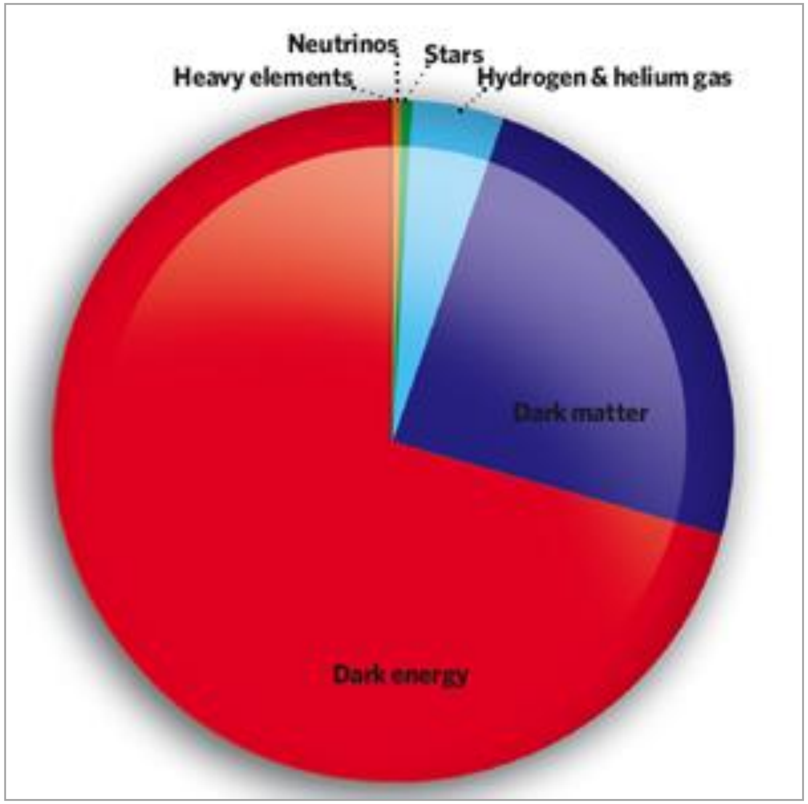
Experiment: **No SUSY particles** (yet)!

Introduction – Current Status



Maybe there is an even deeper level? – „**String Theory**“

Introduction – Current Status



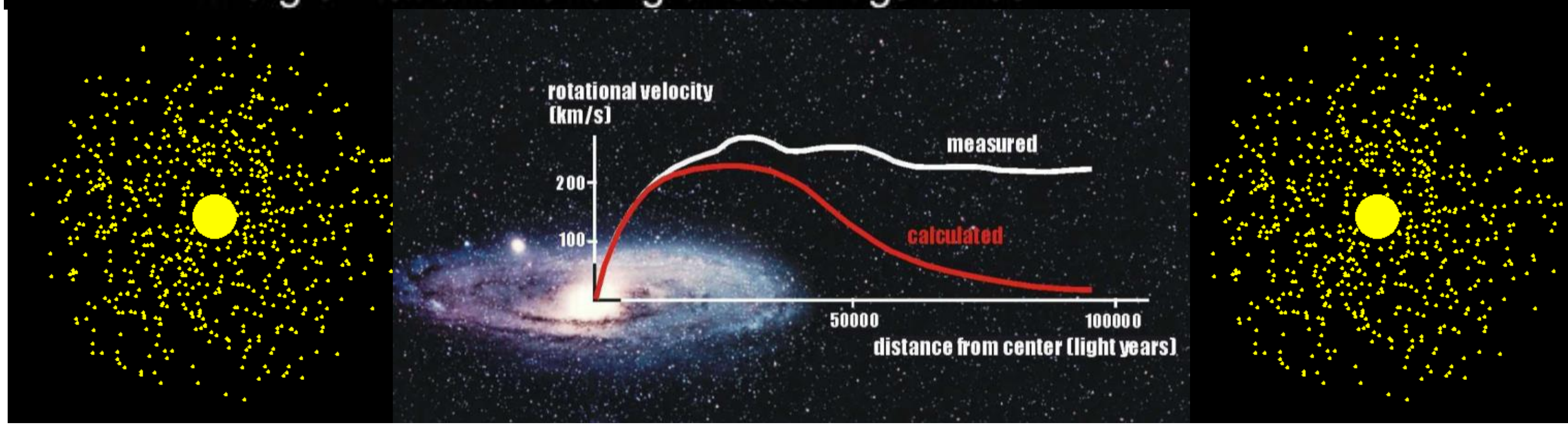
What we know and what we don´t know

What is „Dark Matter“ and „Dark Energy“?

Introduction – Current Status

Dark Matter is matter that emits or reflects minimal to no light, but does have a gravitational influence. Evidence for dark matter appears to be present in

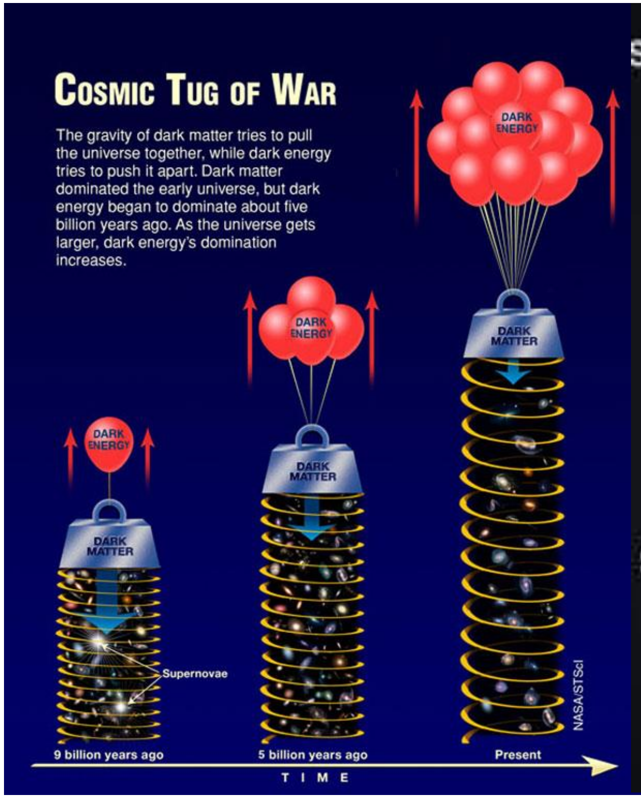
- the motion of stars in galaxies.
- the orbits of galaxies in galaxy clusters.
- the temperature of intracluster gas in galaxy clusters.
- the gravitational lensing of distant galaxies.

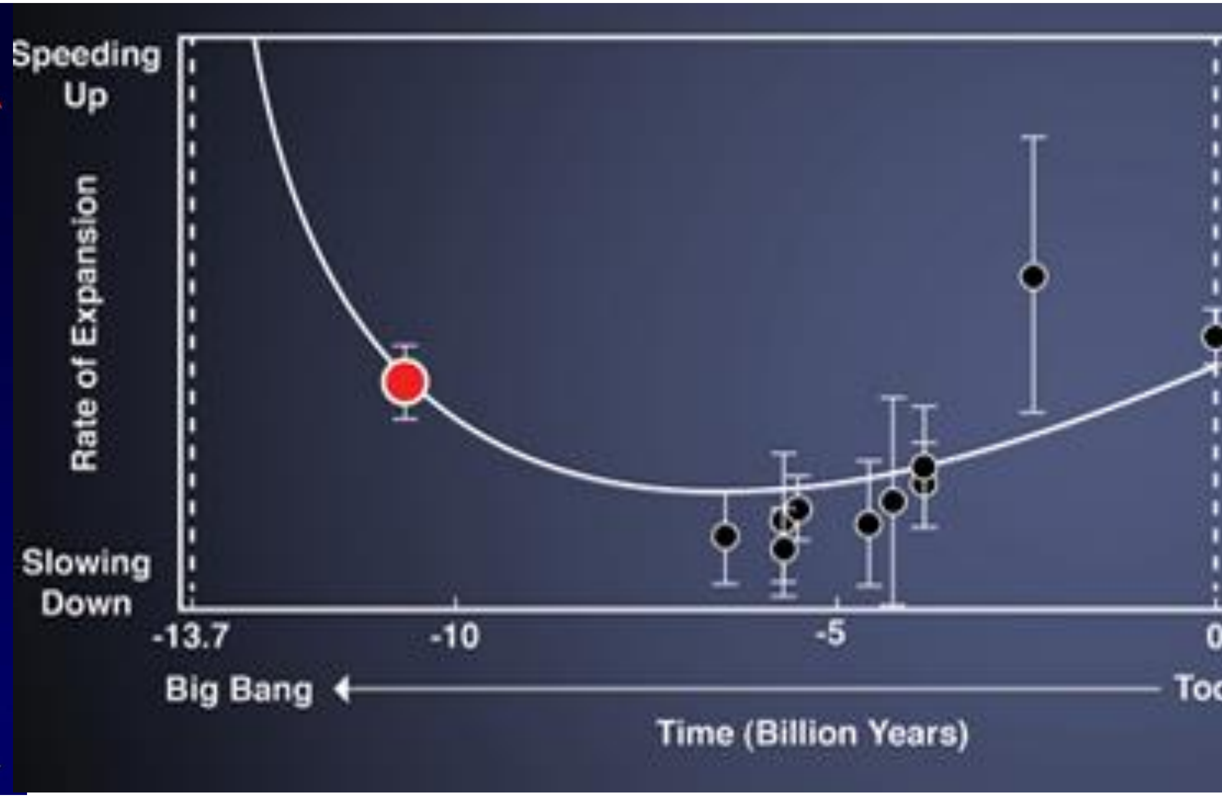


What we know and what we don´t know

„Dark Matter“

Introduction – Current Status

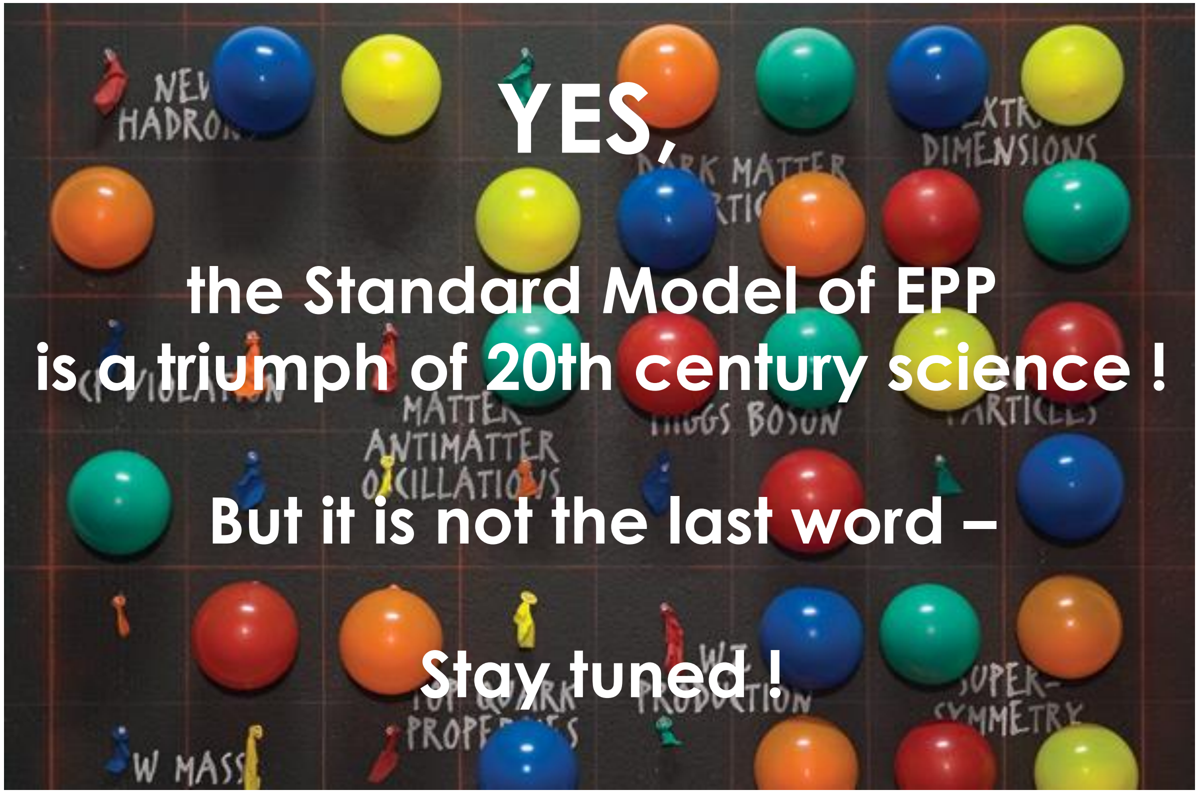




What we know and what we don´t know

„**Dark Energy**“ (accelerating universe)

Introduction – Current Status



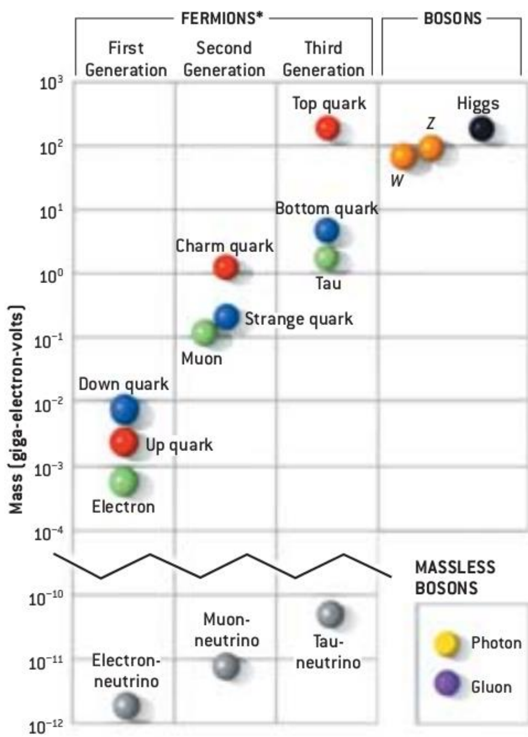
The Standard Model is the „low-energy-limit“ of a more fundamental theory

Beyond Standard Model – General

Necessity for improvements of the Standard Model:

- Steven Weinberg (*Physics Today*, Aug. 2011):

„It is clearly necessary to go beyond the standard model. There is a mysterious spectrum of quark and lepton masses … that we have been staring at for decades … without our being able to interpret them. Also something … is needed to account for cosmological dark matter.“

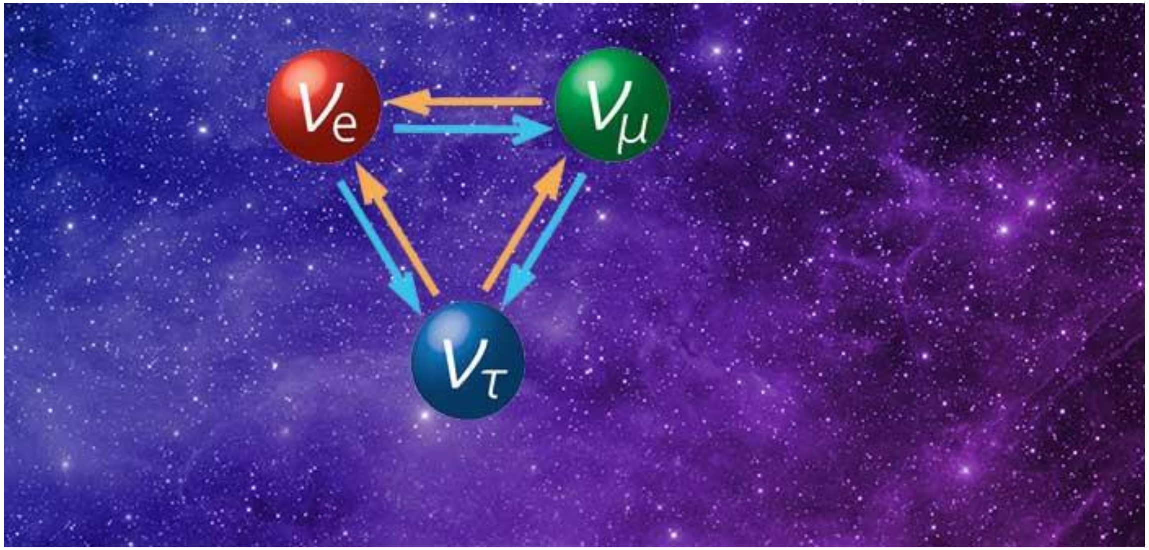


Beyond Standard Model – General

Necessity for improvements of the Standard Model:

- Steven Weinberg (*Physics Today*, Aug. 2011):

„In recent years we have found evidence that there is a new mass scale somewhere in the neighborhood of 10^{16} GeV. (…) In fact the discovery of tiny neutrino masses indicates that the standard model must be supplemented. …“



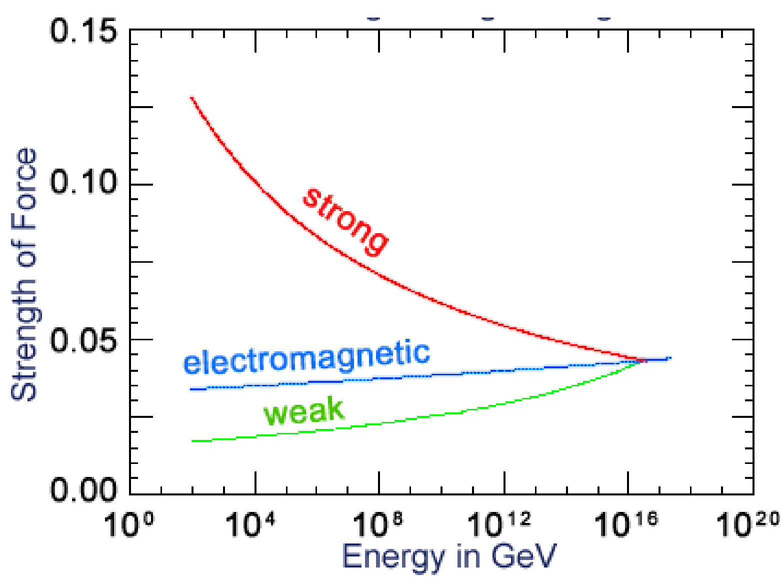
Neutrino oscillations

Beyond Standard Model – General

Necessity for improvements of the Standard Model:

- Steven Weinberg (*Physics Today*, Aug. 2011):

„Of course … we knew of something else beyond the standard model that suggests new physics at masses a little above 10^{16} GeV: the existence of gravitation. And there is also the fact that the one strong and the two electroweak coupling parameters of the standard model … seem to converge to a common value at an energy of the order 10^{15} to 10^{16} GeV.“



Forces merge at high energy

Beyond Standard Model – General

Permanent **Electric Dipole Moments** (EDM) of particles:

Cosmic significance:

> "We must regard it rather as an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about."
>
> **P.A.M. Dirac**, 1933 Noble Talk

Our universe pocesses a huge **matter-antimatter asymmetry**, which cannot be explained within the observed SM **CP-violation**:

Beyond Standard Model – General

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Beyond Standard Model – Our Project

Search for Electric Dipole Moments using Storage Rings (srEDM)

erc European Research Council — Established by the European Commission

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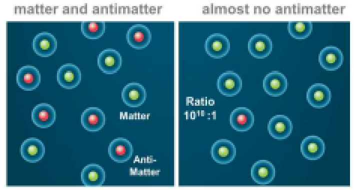
Scientific Background

Matter-Antimatter Asymmetry of the Universe

What we **should see** and what we **actually observe**

equal amount of matter and antimatter | predominantly matter almost no antimatter

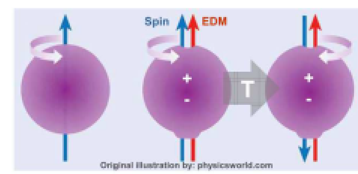


This is one of the big unsolved problems in physics !

Electric Dipole Moments (EDM)

EDMs violate CP – new CP-V provides a possible solution

Electric Dipole Moments violate P- and T-invariance



Via CPT theorem, T-violation corresponds to CP-violation

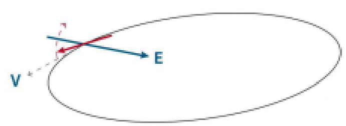
Experimental Approach

Charged Particle EDM Search

EDMs are searched for in electrons, neutrons, atoms and molecules, to date without success – only upper limits were obtained; the **srEDM** (protons, deuterons) will **improve** these limits **significantly** or even **find** an **EDM**

Measurement principle

Particle spin alignment along momentum (*frozen spin*)

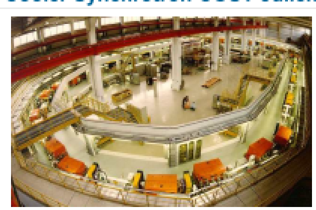


Radial E-field: torque on spin – rotation out of ring plane

Precursor Experiment

In a stepwise approach, starting from R&D for all crucial tools required, proof-of-principle measurements at COSY-Jülich will be conducted, leading to **first** directly determined **upper EDM limits** for the **deuteron** and/or the **proton**

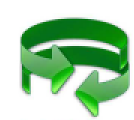
Cooler Synchrotron COSY-Jülich



Outlook: Dedicated EDM Ring

For the EDM search with highest sensitivity, a completely new **high-precision double storage** ring is required aiming at **10^{-29} e·cm** – a charge separation of **~1 nanometer (if nucleon had the size of the earth!)**

Counter-rotating beams



Purely **electric deflection** (pEDM only)
→ two separated beams simultaneously
Combined **electric/magnetic deflection** (pEDM and dEDM ...)
→ two separated beams simultaneously
or one beam at a time and B-field reversal

ERC AdG «srEDM» (Grant 694340): ~2.4 M€ for 5 Years, Start 2016

გმადლობთ