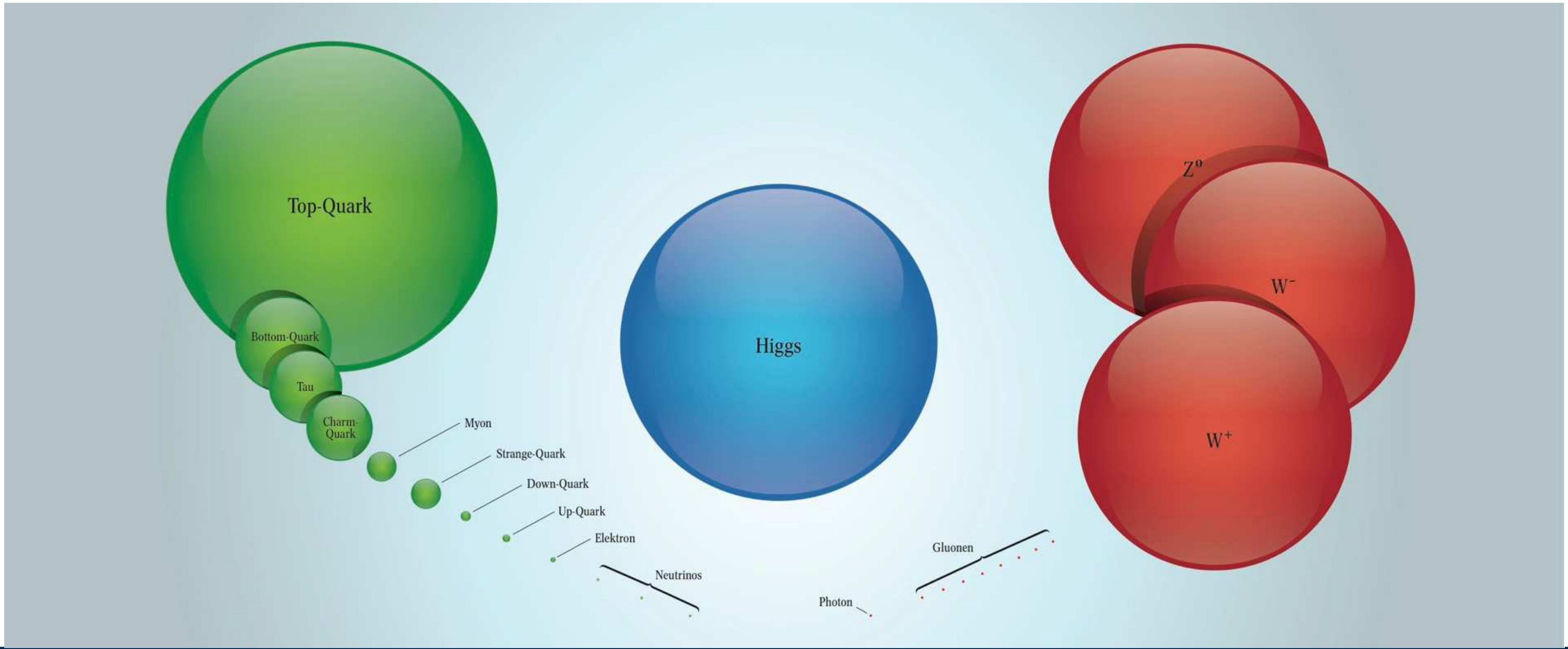



# ELEMENTARY PARTICLE PHYSICS

## A BRIEF INTRODUCTION (PART II)

APRIL 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)



JÜLICH
Forschungszentrum

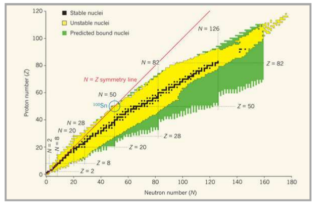
# Outline – EPP Video Lectures

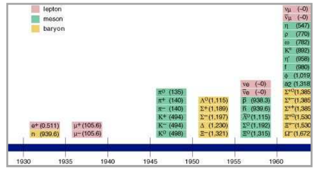
- An introduction of Elementary Particle Physics (EPP) via video
- Lecturers: Hans Ströher, Irakli Keshelashvili, Detlev Gotta
- Time: Monday & Friday @ 3 pm (Jülich time) → 5 pm (Tbilisi)
- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … kinematics, …)
  - The **particles** (hadrons, baryons, mesons)
  - The ***fundamental* particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear forces)
  - The ***fundamental* interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

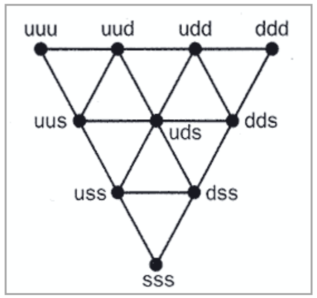
**Overall Information**

# Introduction – Part I

- EPP as curiosity-driven basic research
- Connection between the very-large and the very-small
- Table of elements
- Discovery of electron, proton, neutron
- Table of isotopes
- Antiparticles
- Particle „zoo“
- Quarks (up, down, strange)

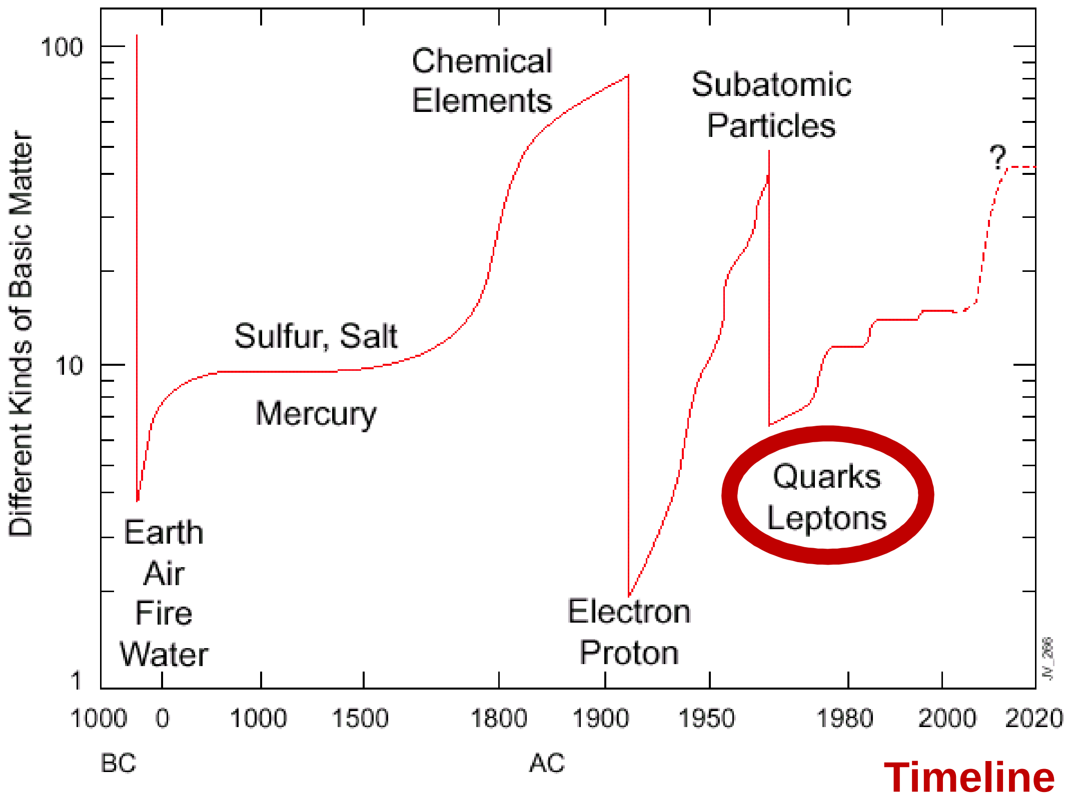






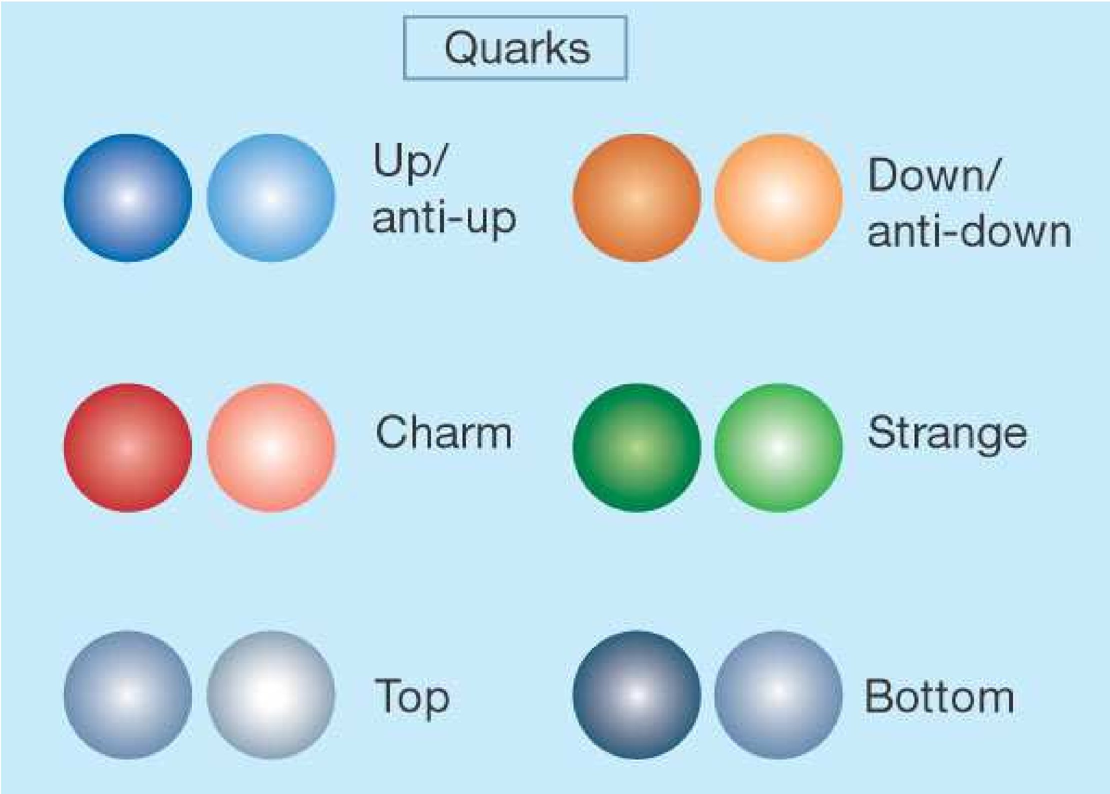

**Recap Introduction (Part I)**

# Introduction – History



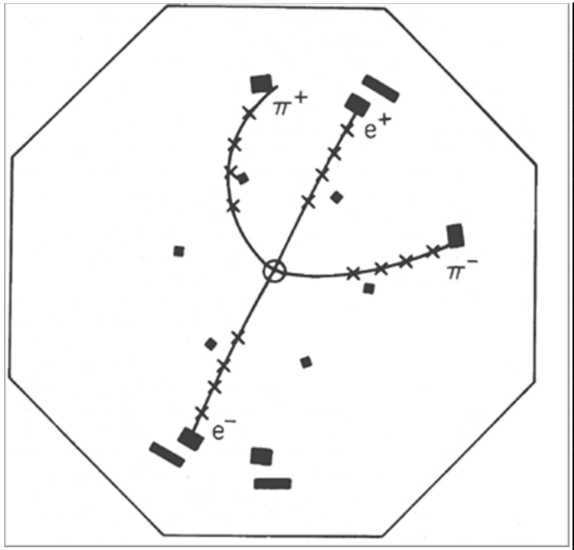

**The up´s and down´s in the number of matter constituents**

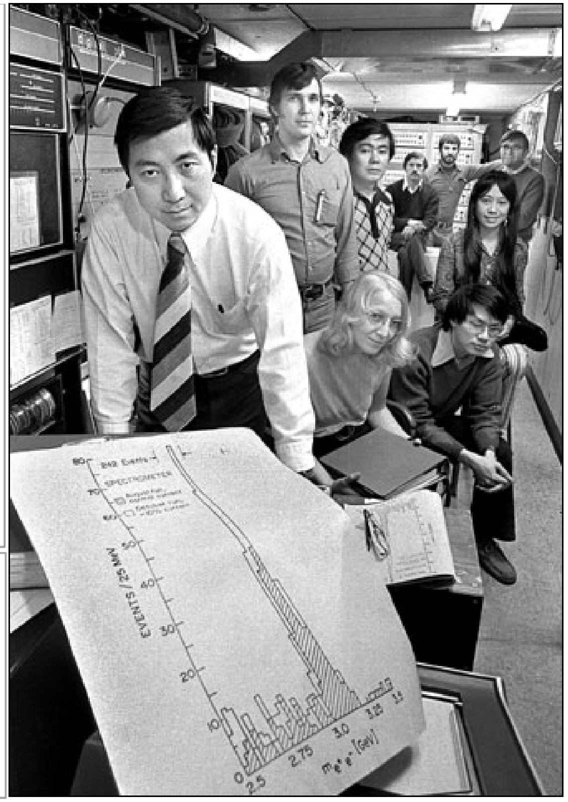
# Introduction – History




Not only „up“ (u), „down“ (d) and „strange“ (s) quarks

# Introduction – History



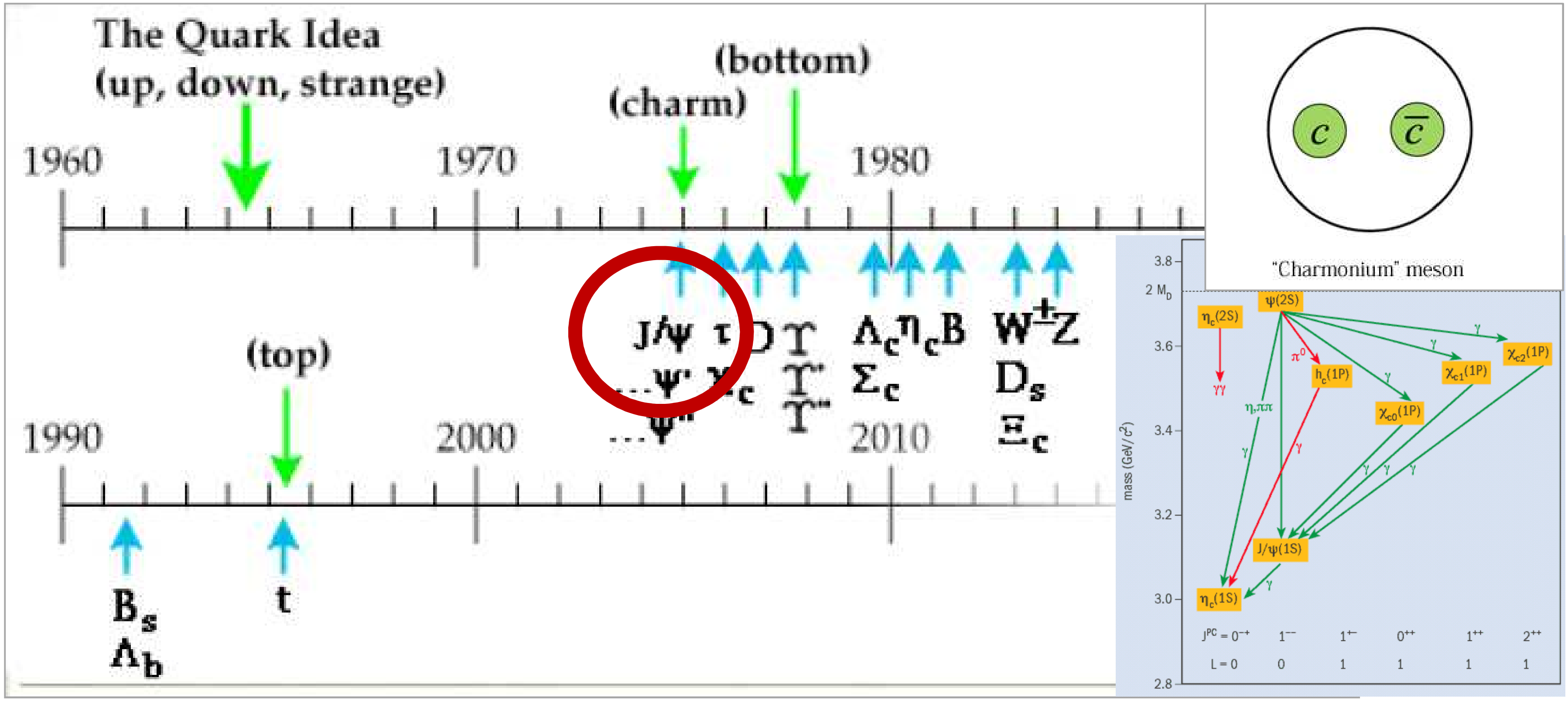
**$J/\psi(1S)$** $\qquad I^G(J^{PC}) = 0^-(1^{--})$

**$J/\psi(1S)$ MASS**

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

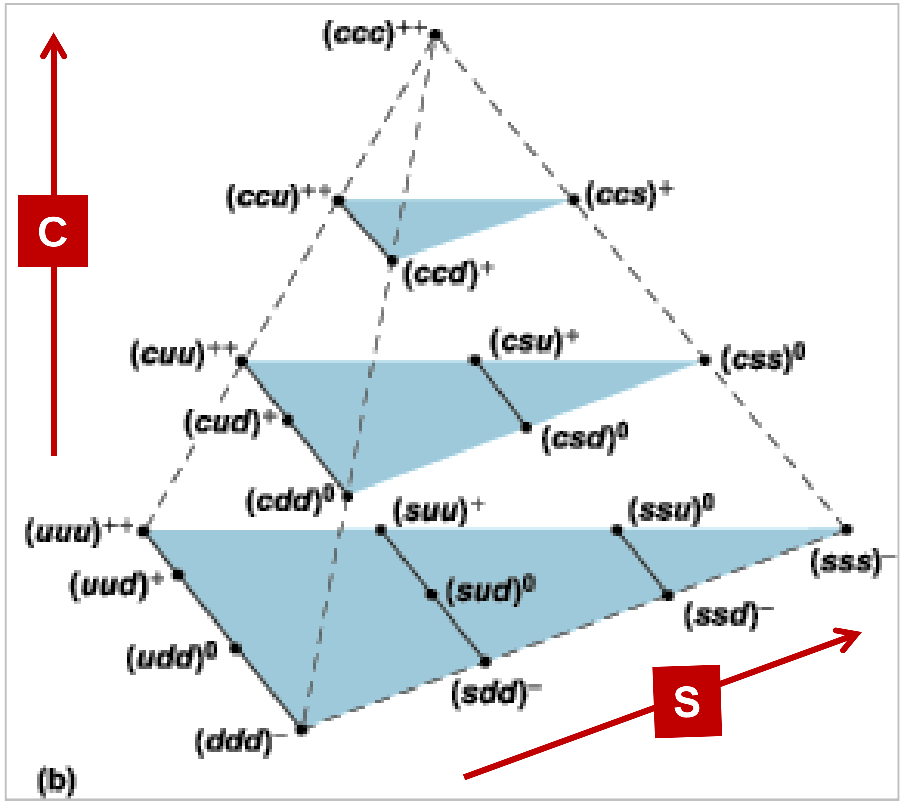
**B. Richter and S. Ting (1974): J/Psi (charm-quark)**

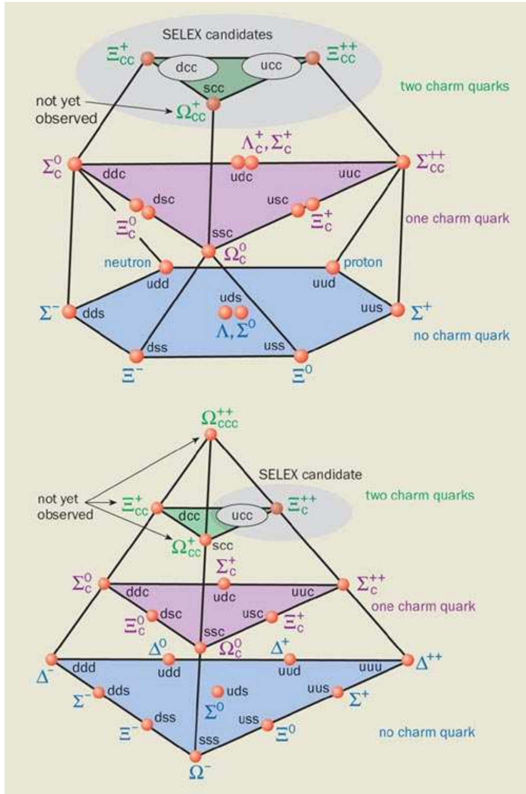
# Introduction – History




Charm quark → „Charmonium"

# Introduction – **History**




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

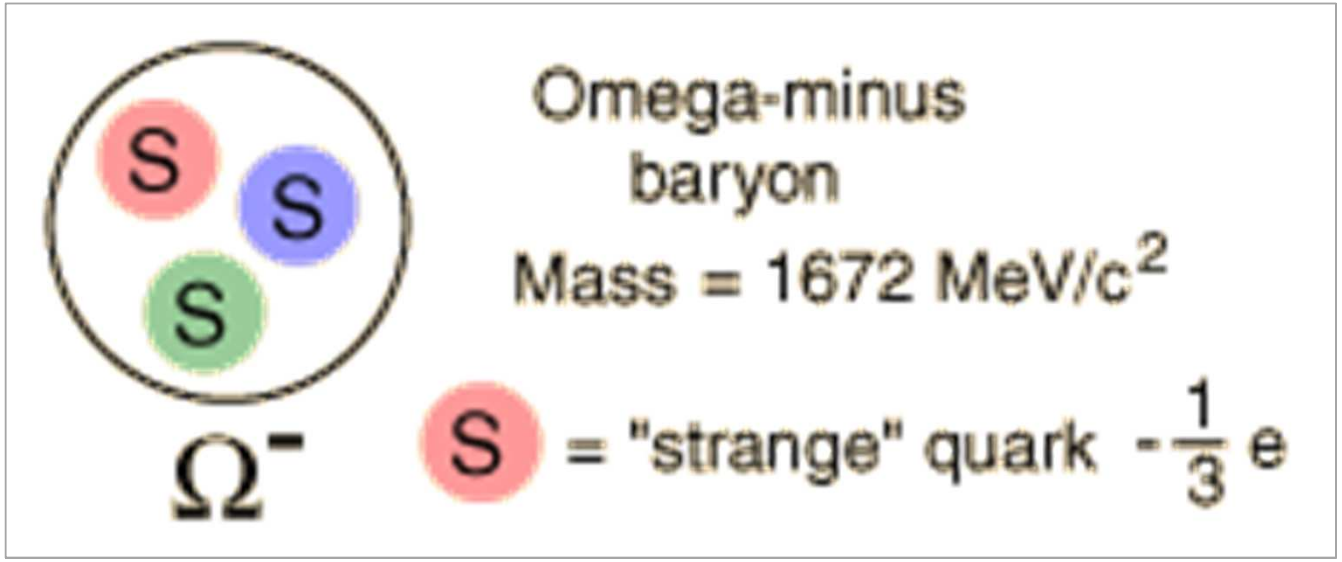
# Introduction – History

| | Fermions | | | Charge ($e_0$) |
|---|---|---|---|---|
| Quarks | *u* up | *c* charm | *t* top | + 2/3 |
| | *d* down | *s* strange | *b* bottom | - 1/3 |
| Leptons | $\nu_e$ electron neutrino | $\nu_\mu$ muon neutrino | $\nu_\tau$ tau neutrino | 0 |
| | e electron | $\mu$ muon | $\tau$ tau | -1 |

→ increasing mass

**Matter** particles (plus: antiparticles) → why 3 generations (families)?

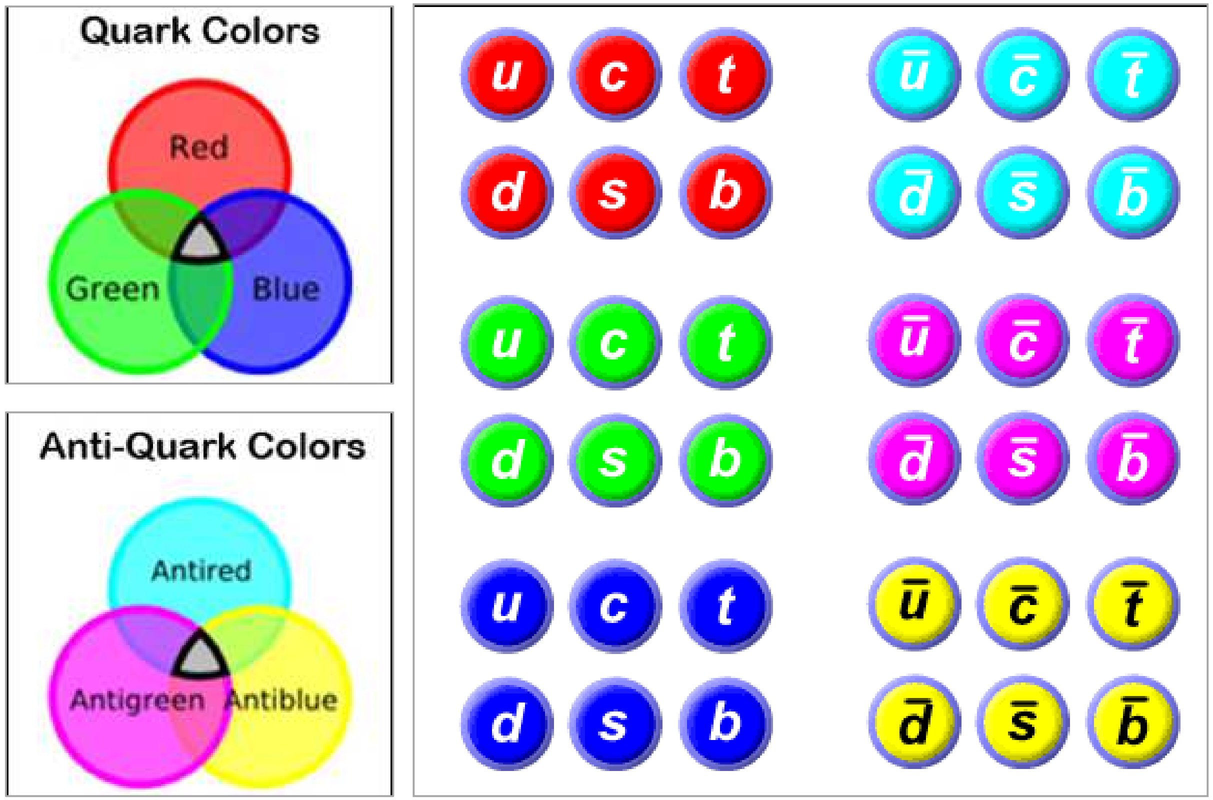
# Introduction – History




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

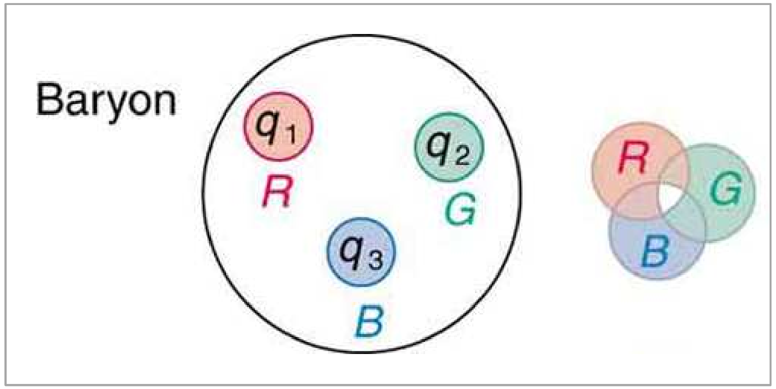
# Introduction – History

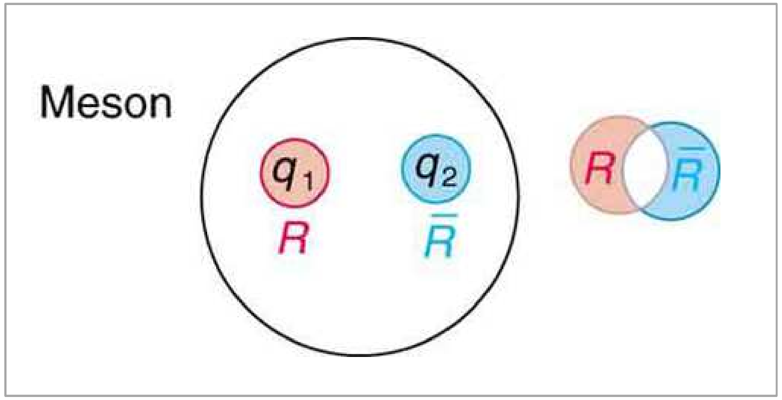



Quarks carry **color**, anti-quarks **anti-color**

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

# Introduction – History

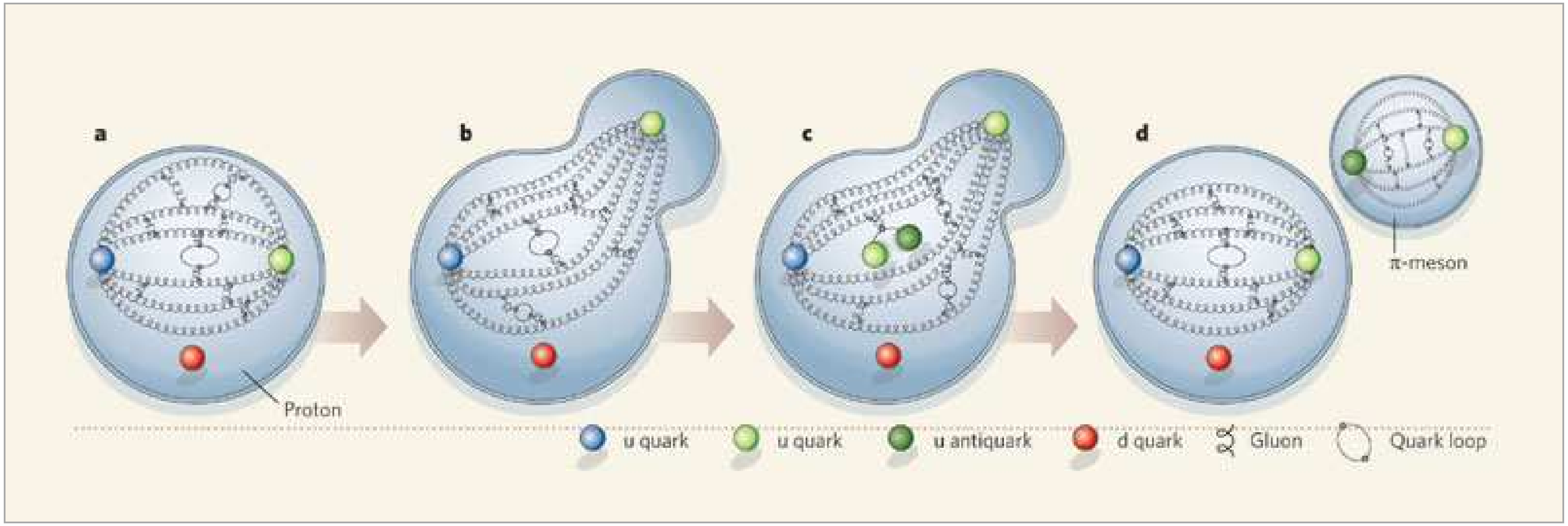



Bound states (hadrons) are **3 quark** or **quark-antiquark**

Hadrons *must be* **color-neutral („white“)**

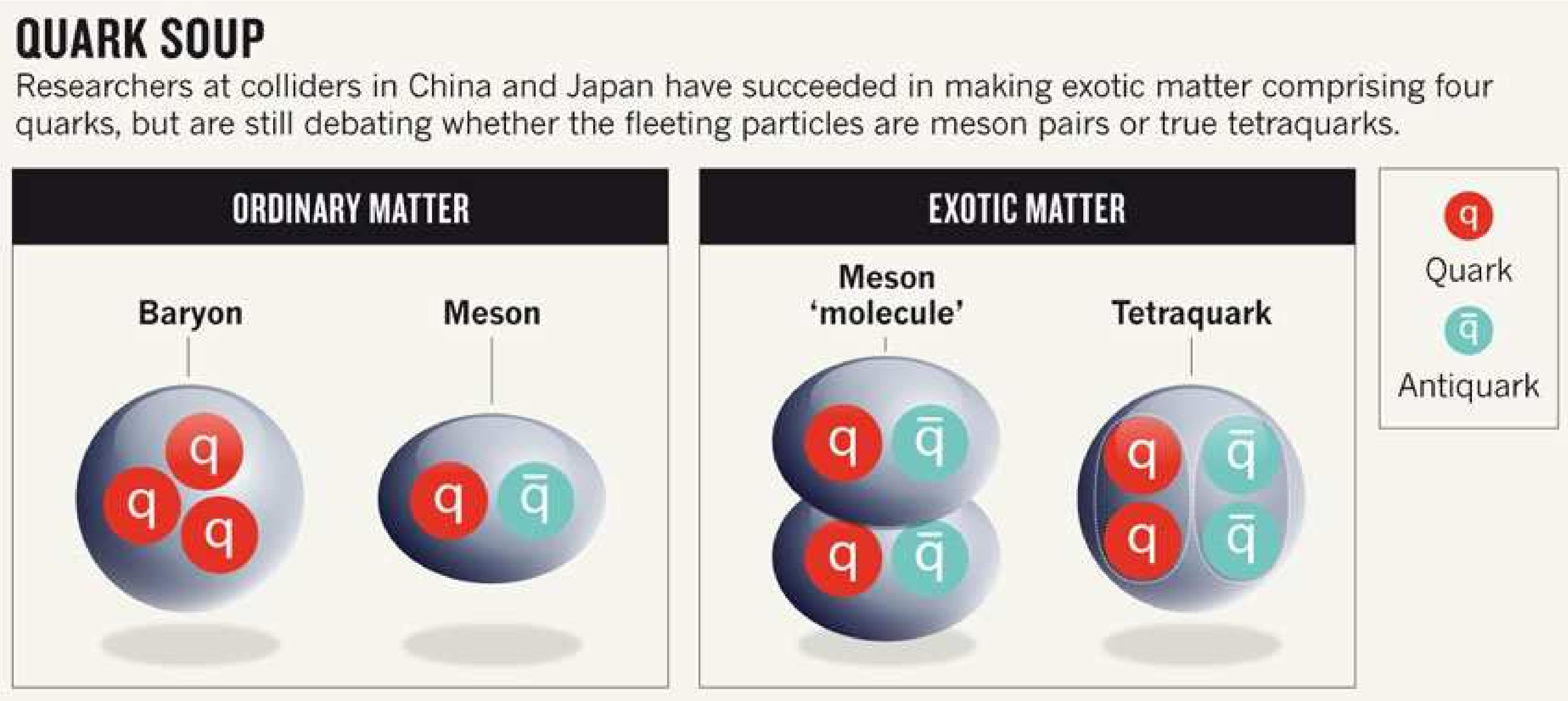
# Introduction – History




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

**No free quarks: „confinement“**

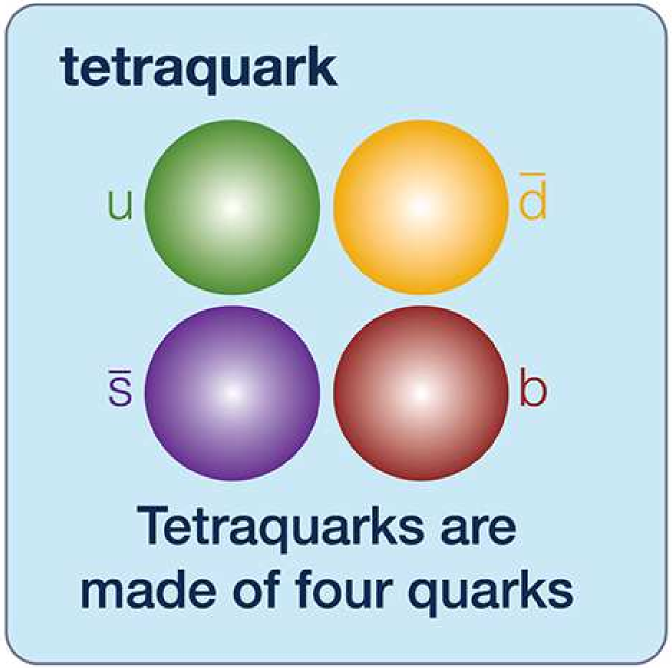
# Introduction – History



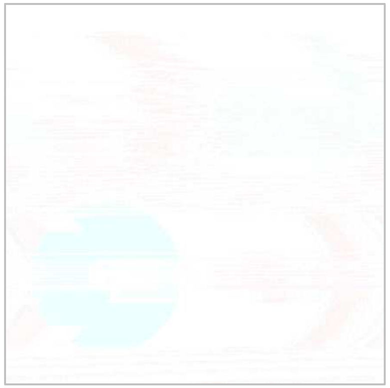

**Bound states (hadrons) are color-neutral ("white")**

Which **hadrons** exist in Nature?

# Introduction – History



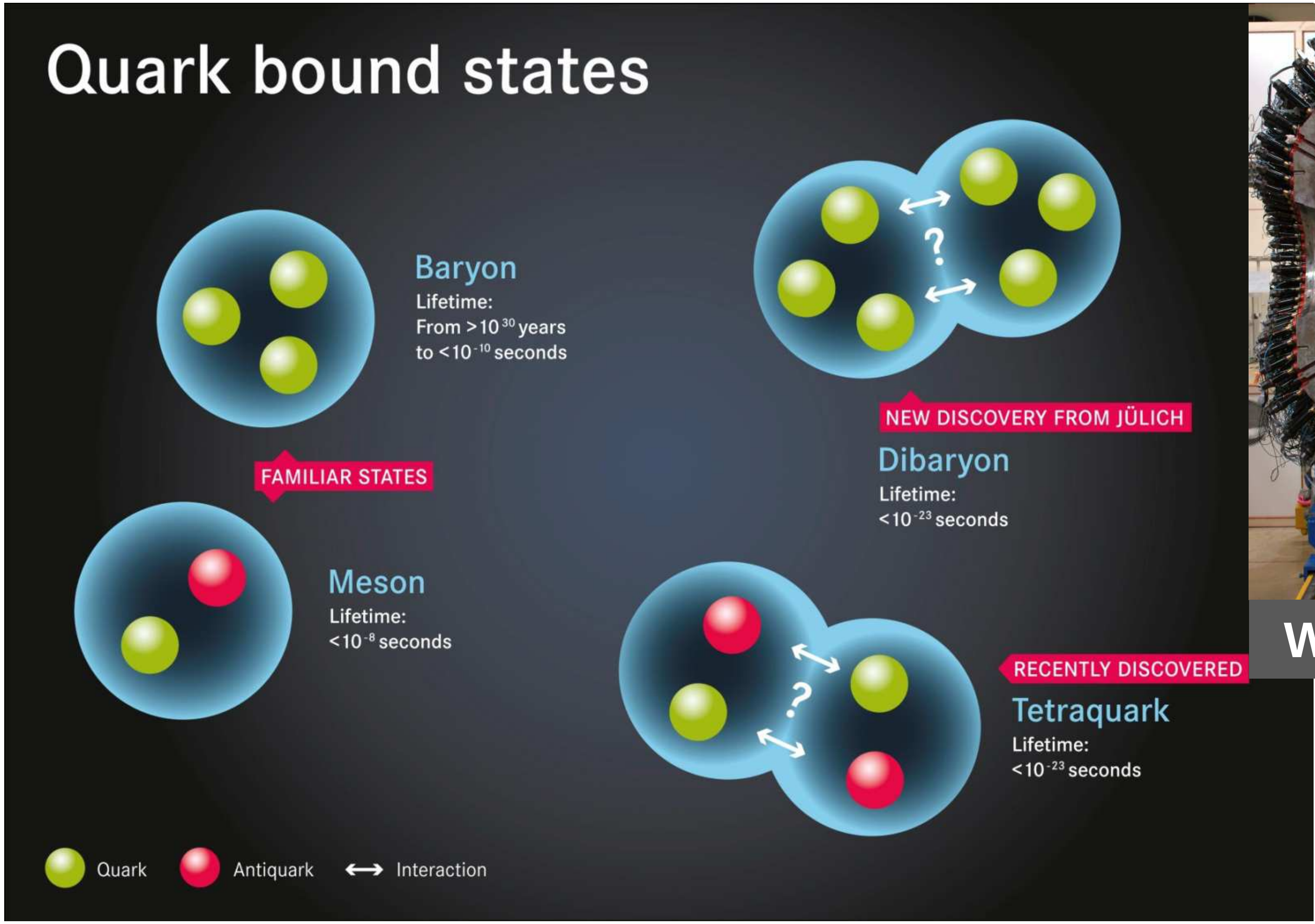

*This is X(5568), which is made of an up, down, strange and bottom quark.*

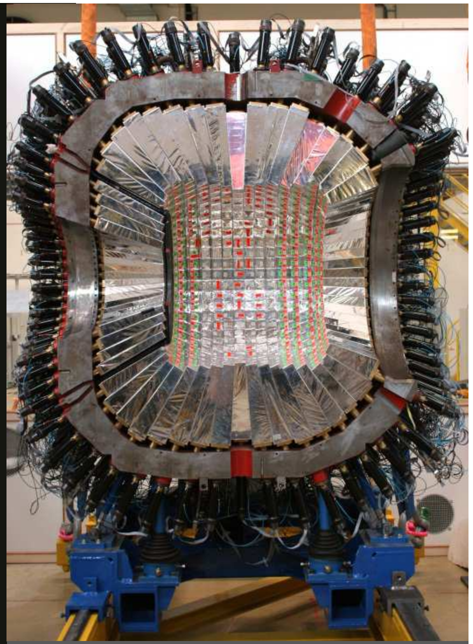


**Color-neutral** quark states

Which **hadrons** exist in Nature?

# Introduction – History

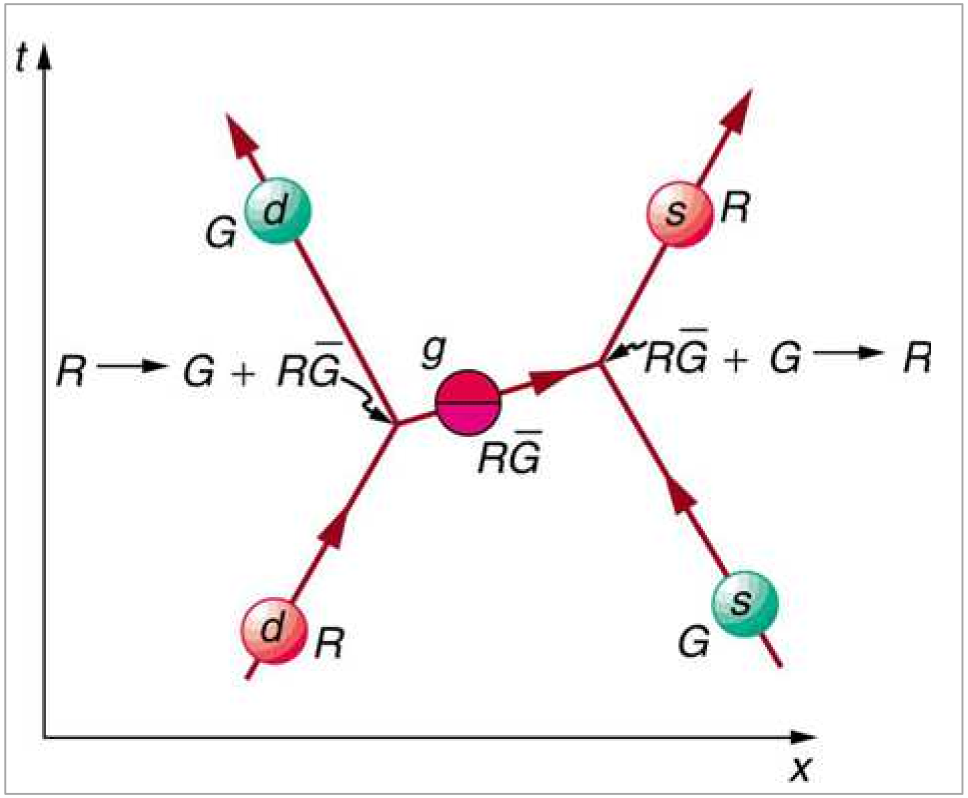


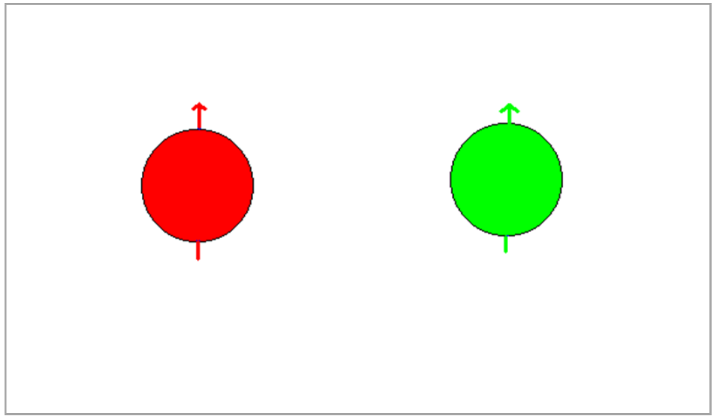
WASA at COSY

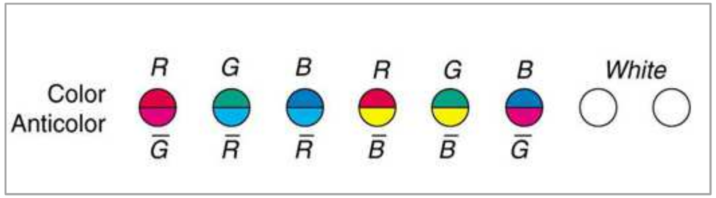
Which **hadrons** exist in Nature?

# Introduction – History




Gluons carry **color-anticolor**

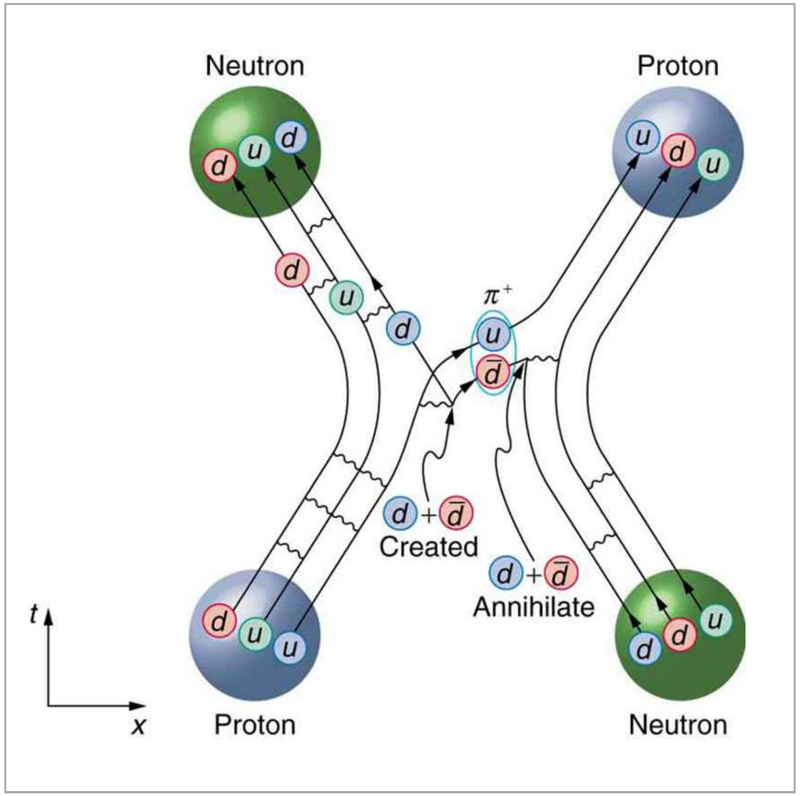





**Strong interaction** between quarks

Strong interaction is mediated by **gluon exchange**

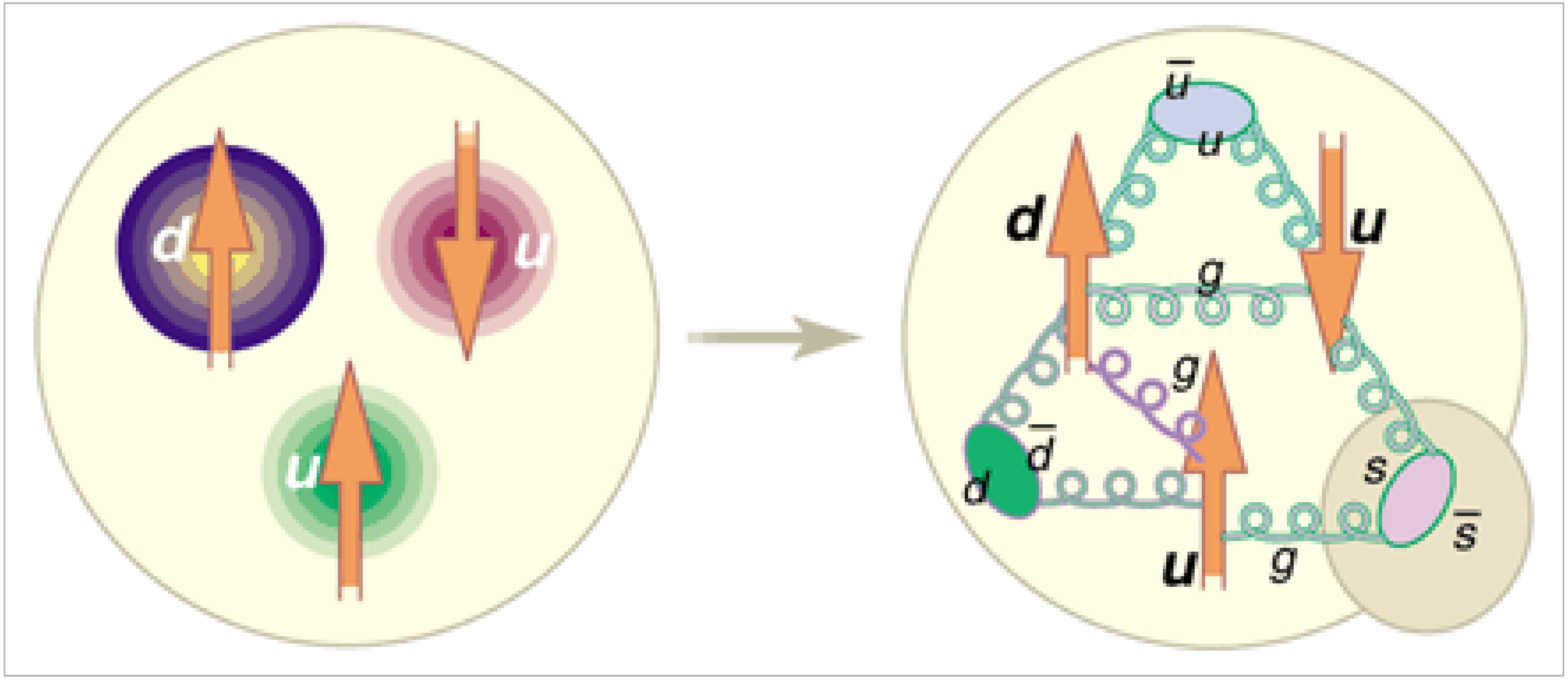
# Introduction – History




Interaction between hadrons

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

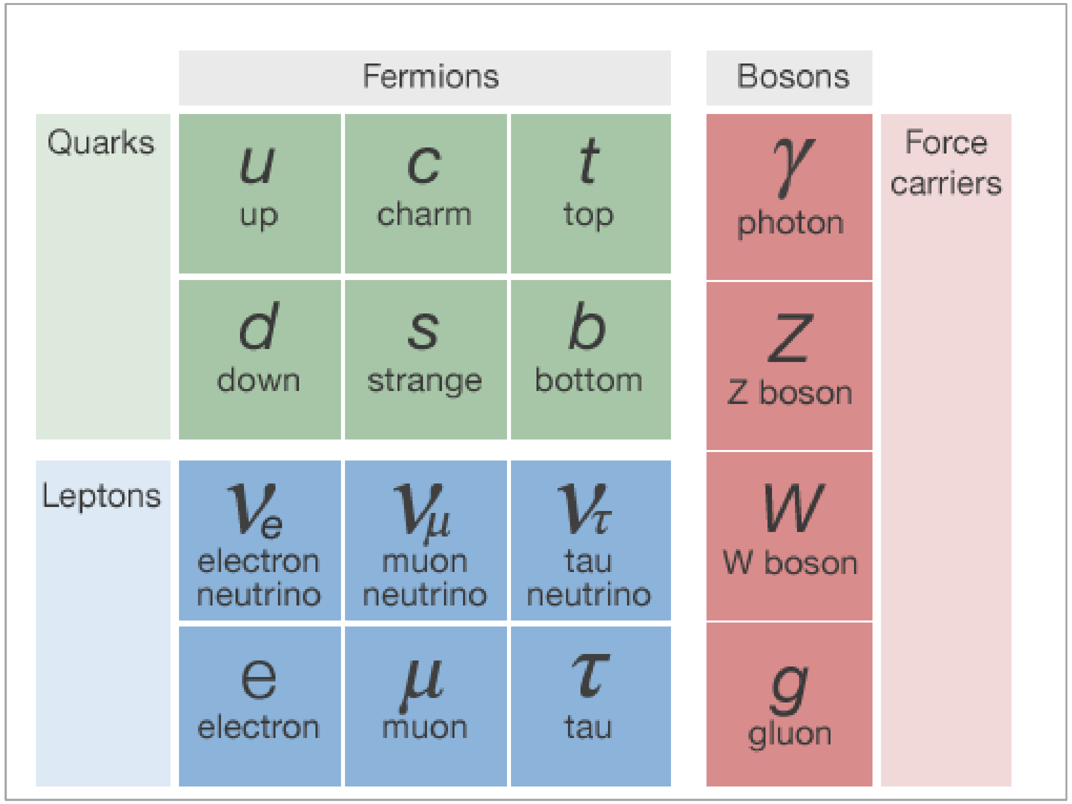
# Introduction – History

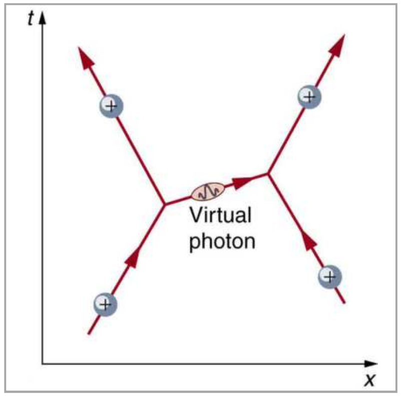


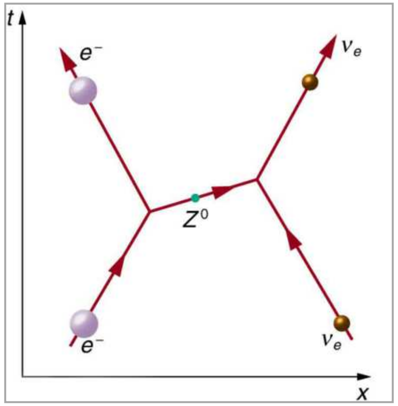

“Constituent quarks” and “sea quarks”

Hadrons (e.g. nucleons) are complex systems

# Introduction – History



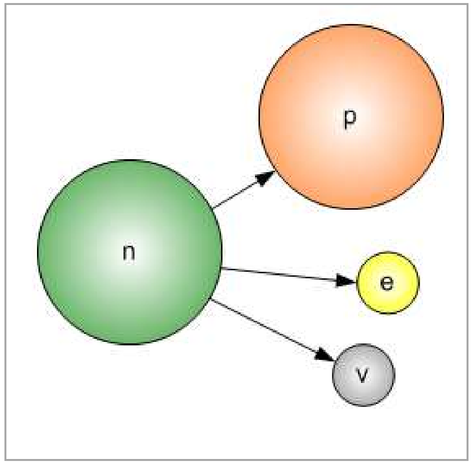



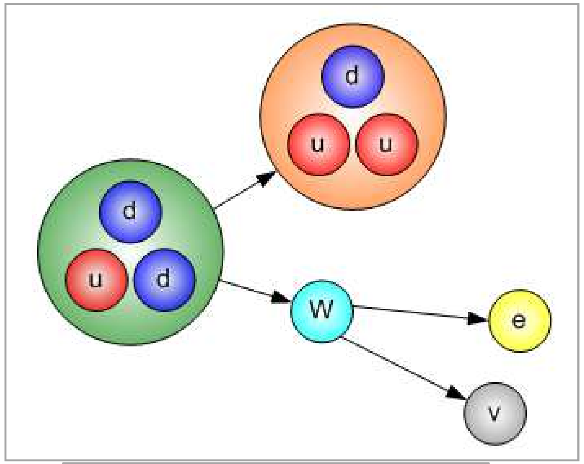



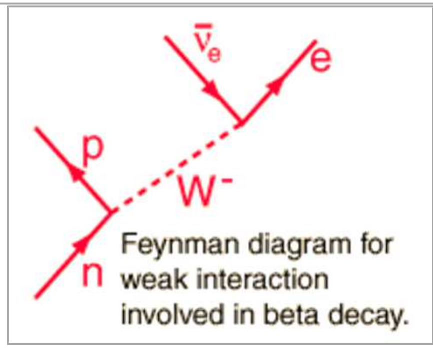

## Force particles

**Interaction mediated by exchange bosons**

# Introduction – History



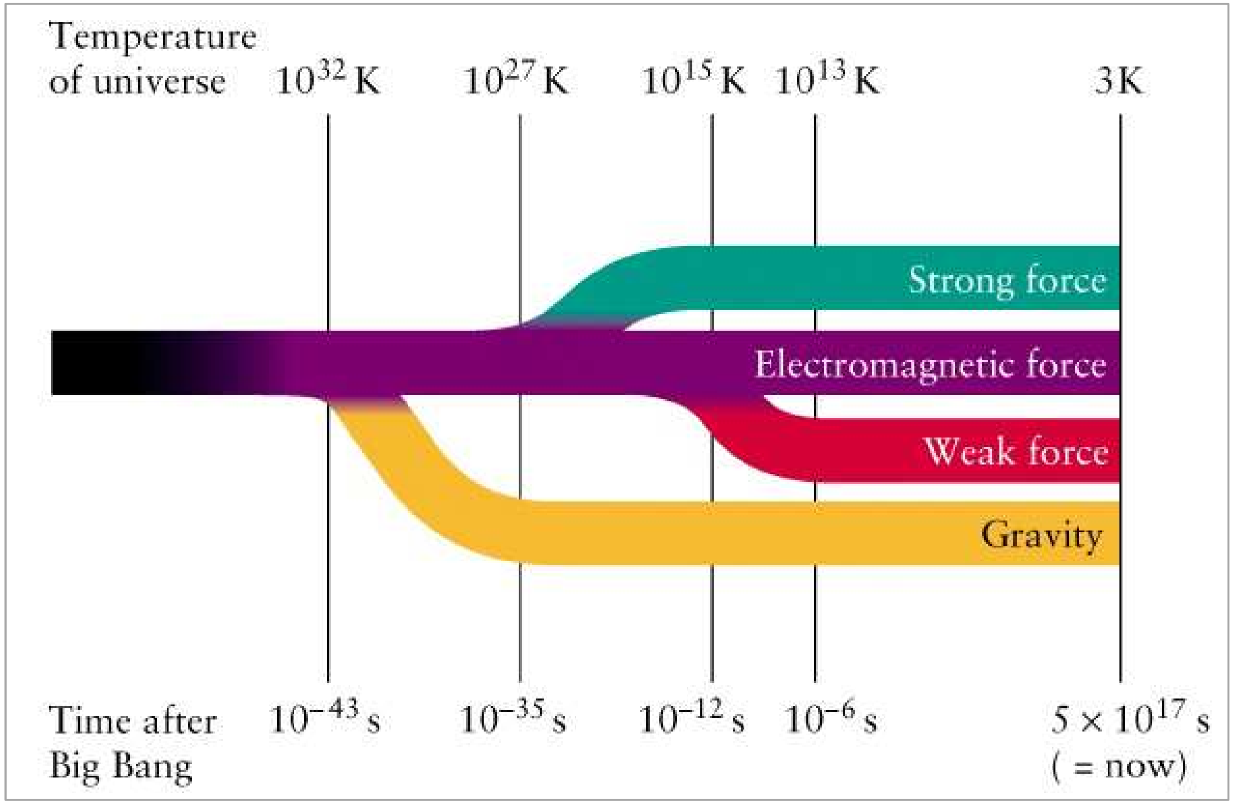



Feynman diagram for weak interaction involved in beta decay.

## **Weak interaction** (example: neutron decay)

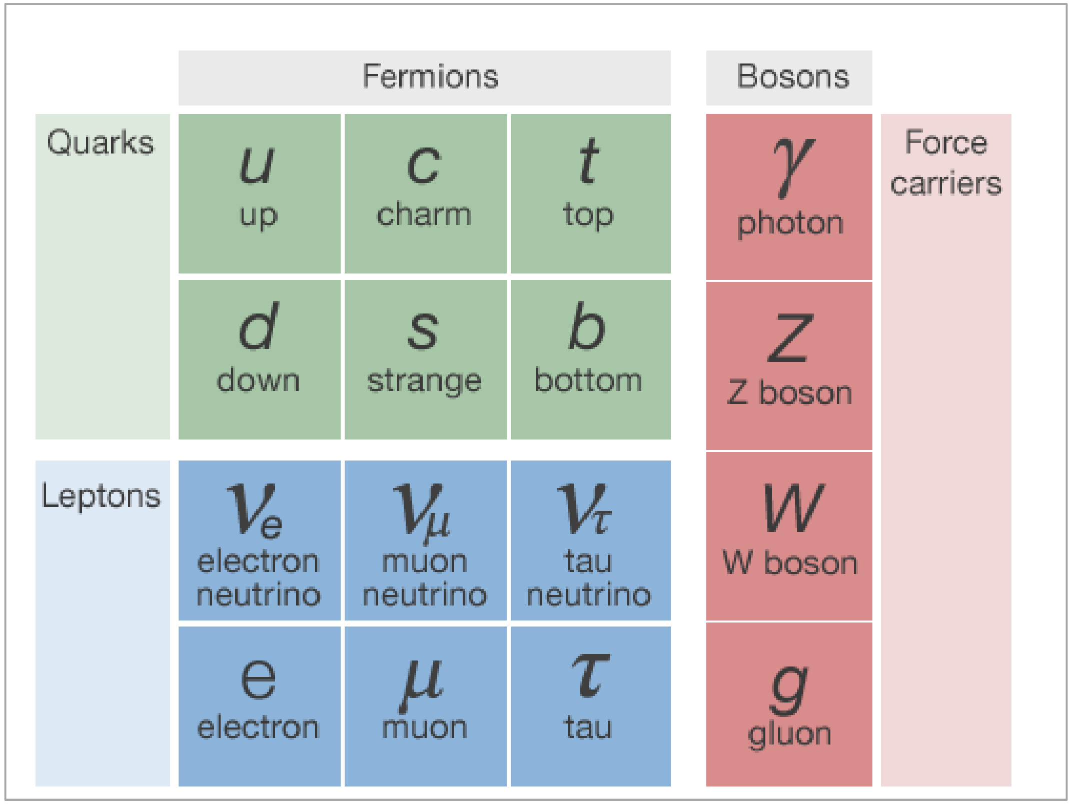
Weak interaction is **special** in many aspects

# Introduction – History




## Unification of forces

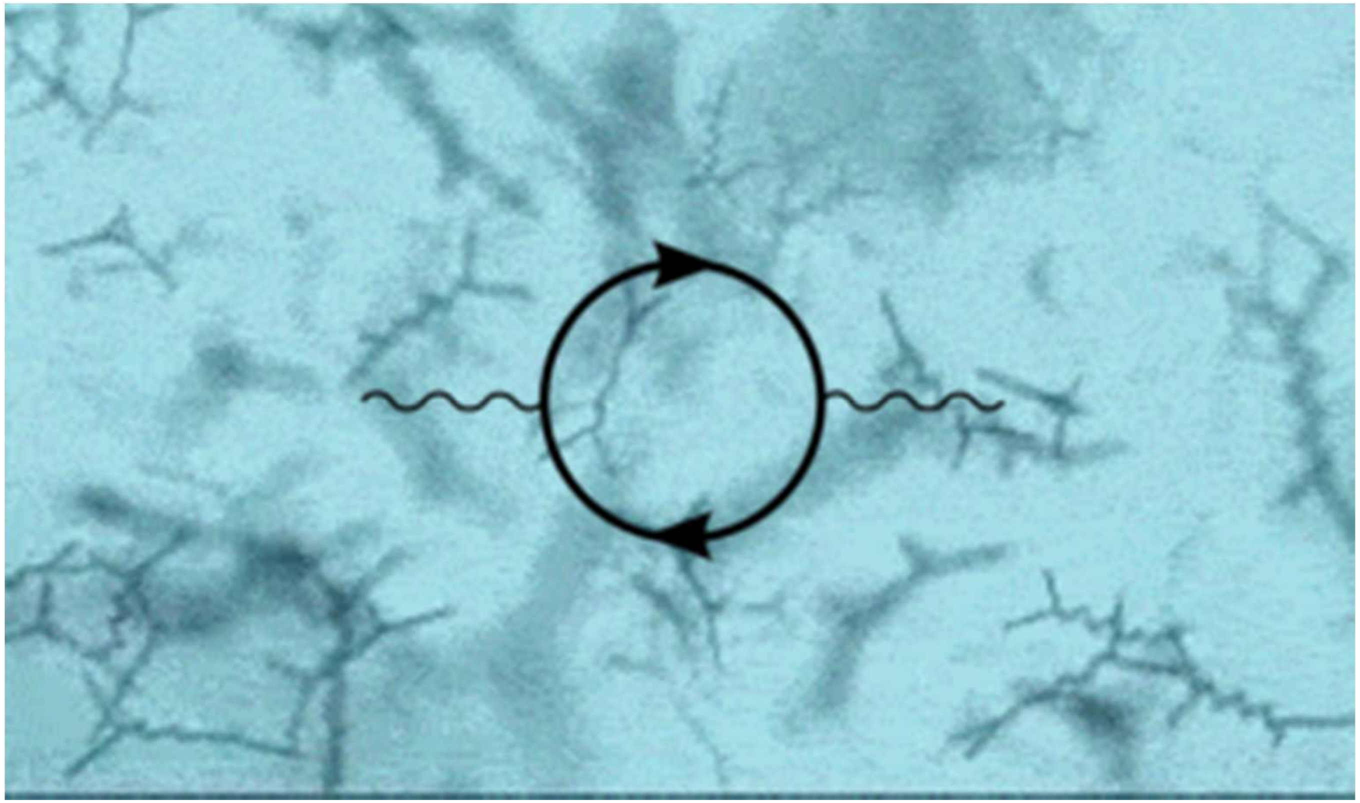
# Introduction – **History**




What gives these particles **(different) mass**?

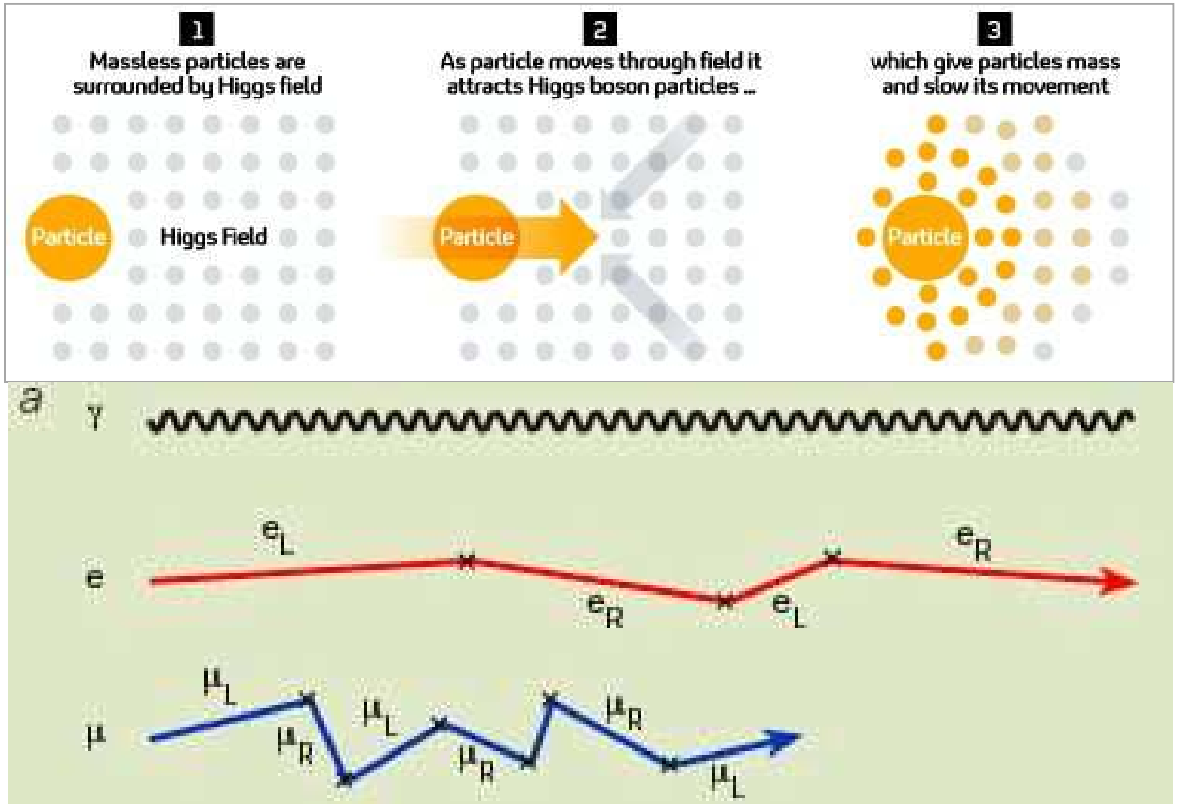
Internal consistency of Standard Model: **Higgs meachanism**

# Introduction – Current Status



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

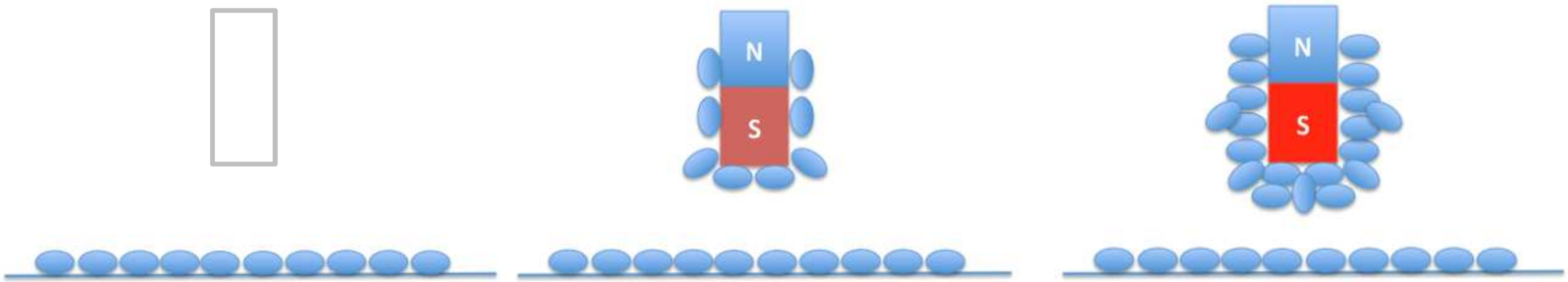
# Introduction – Current Status




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

# Introduction – Current Status

Analogy: think of **dipole** magnets of different strength …

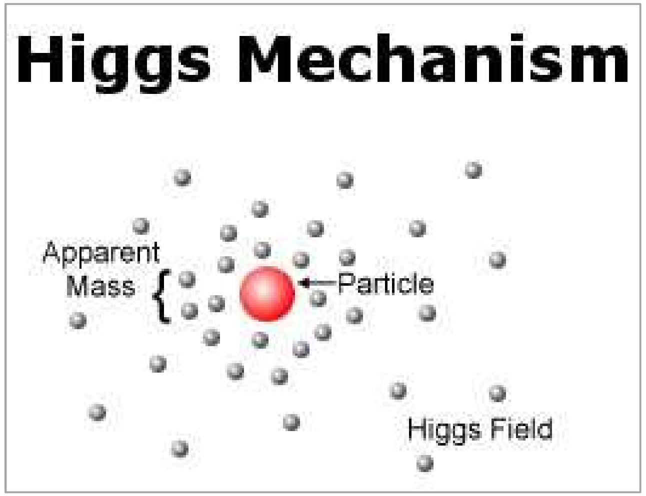


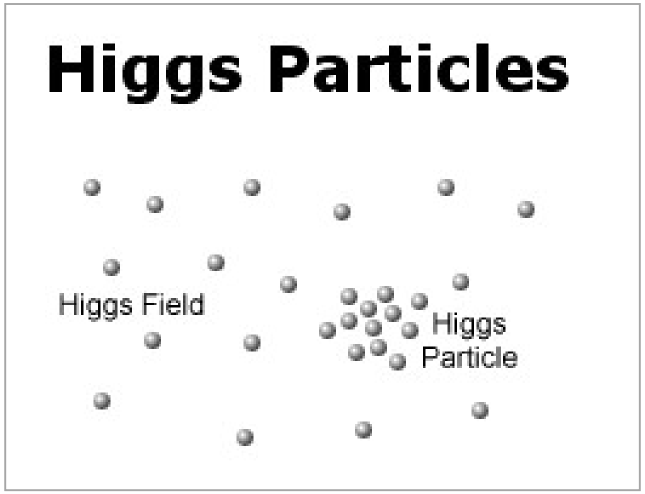

… and a „field“ of magnetized tiny particles …

No mass | Low mass | High mass

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

# Introduction – Current Status

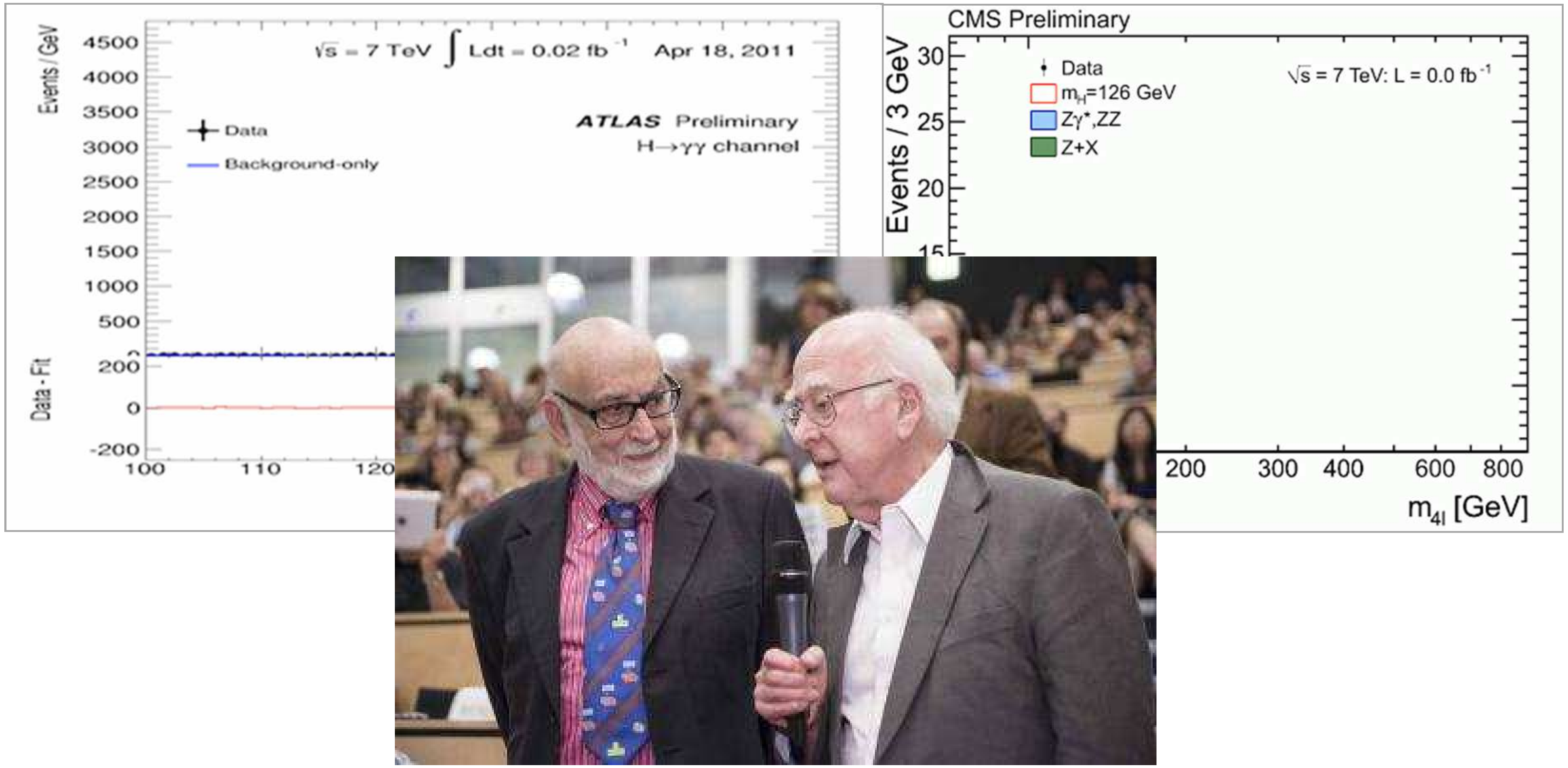



## Higgs boson

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

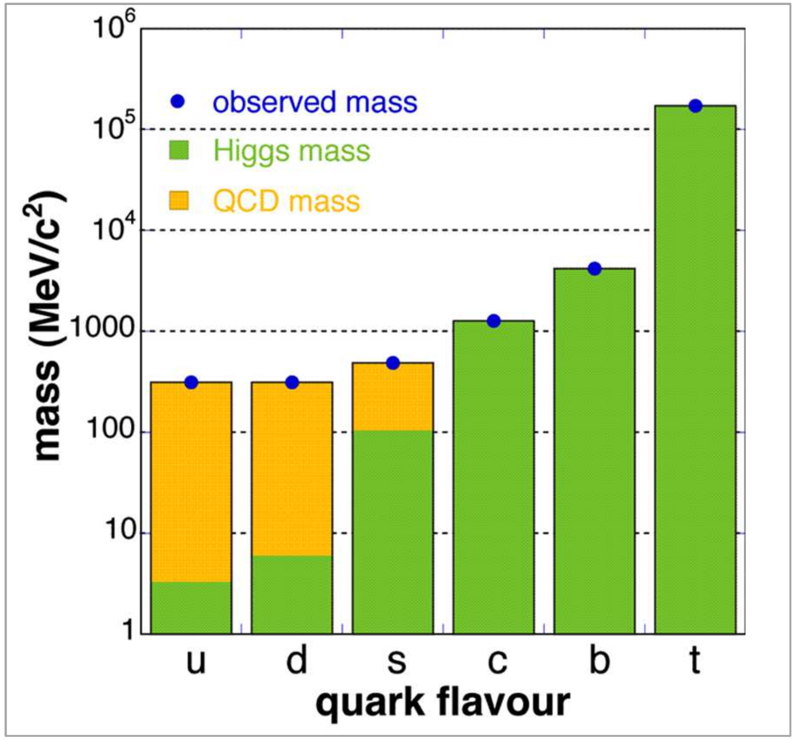
# Introduction – Current Status




## Higgs boson

**Prediction (1964) and discovery (2012) of the Higgs-Boson**

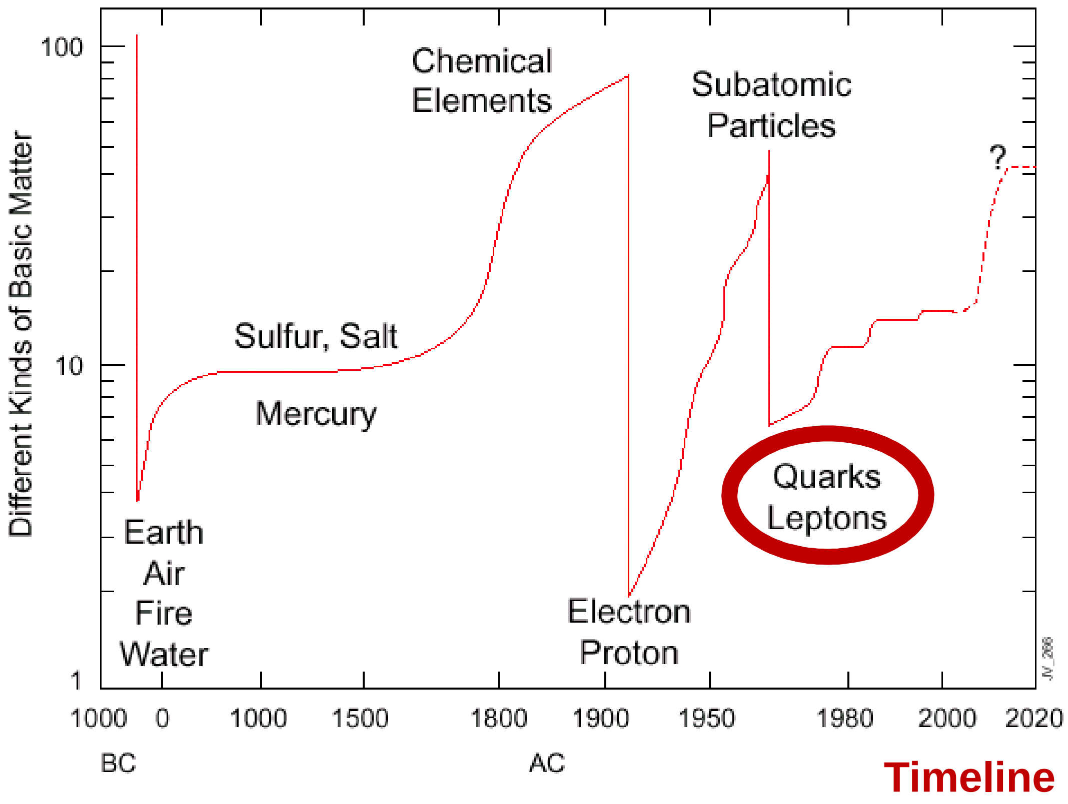
# Introduction – Current Status




**Higgs mechanism** contributes differently to quark mass

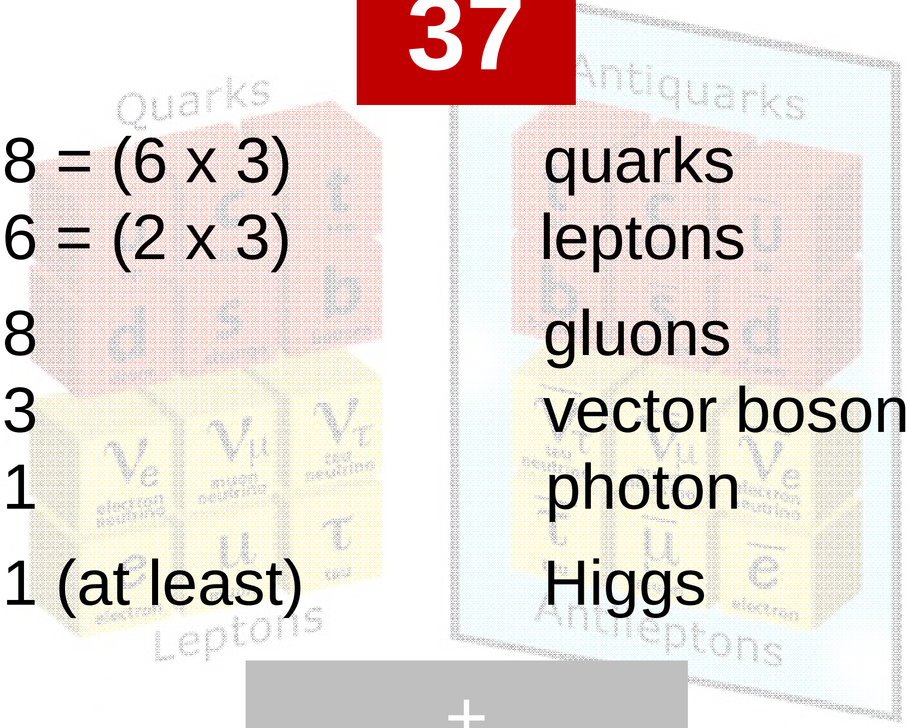
Countless Higgs-Bosons („Higgs-field“) permeate all of the space

# Introduction – Current Status




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

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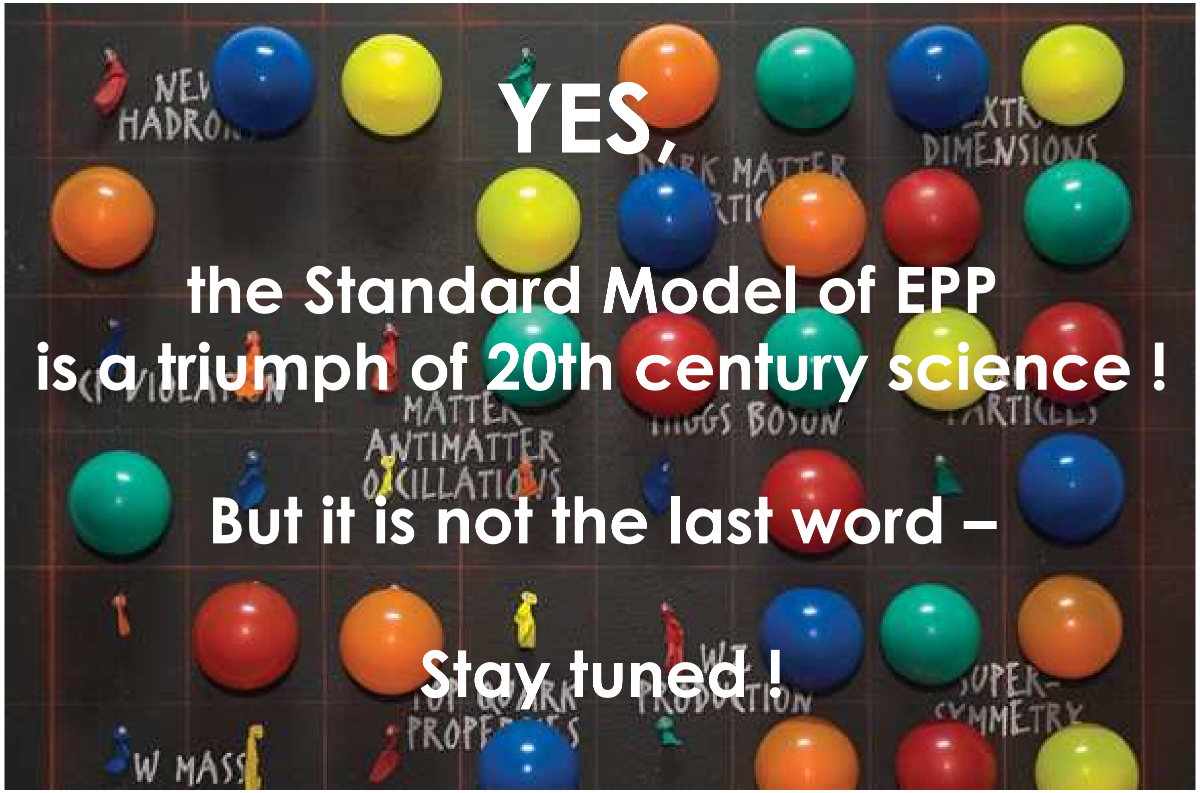
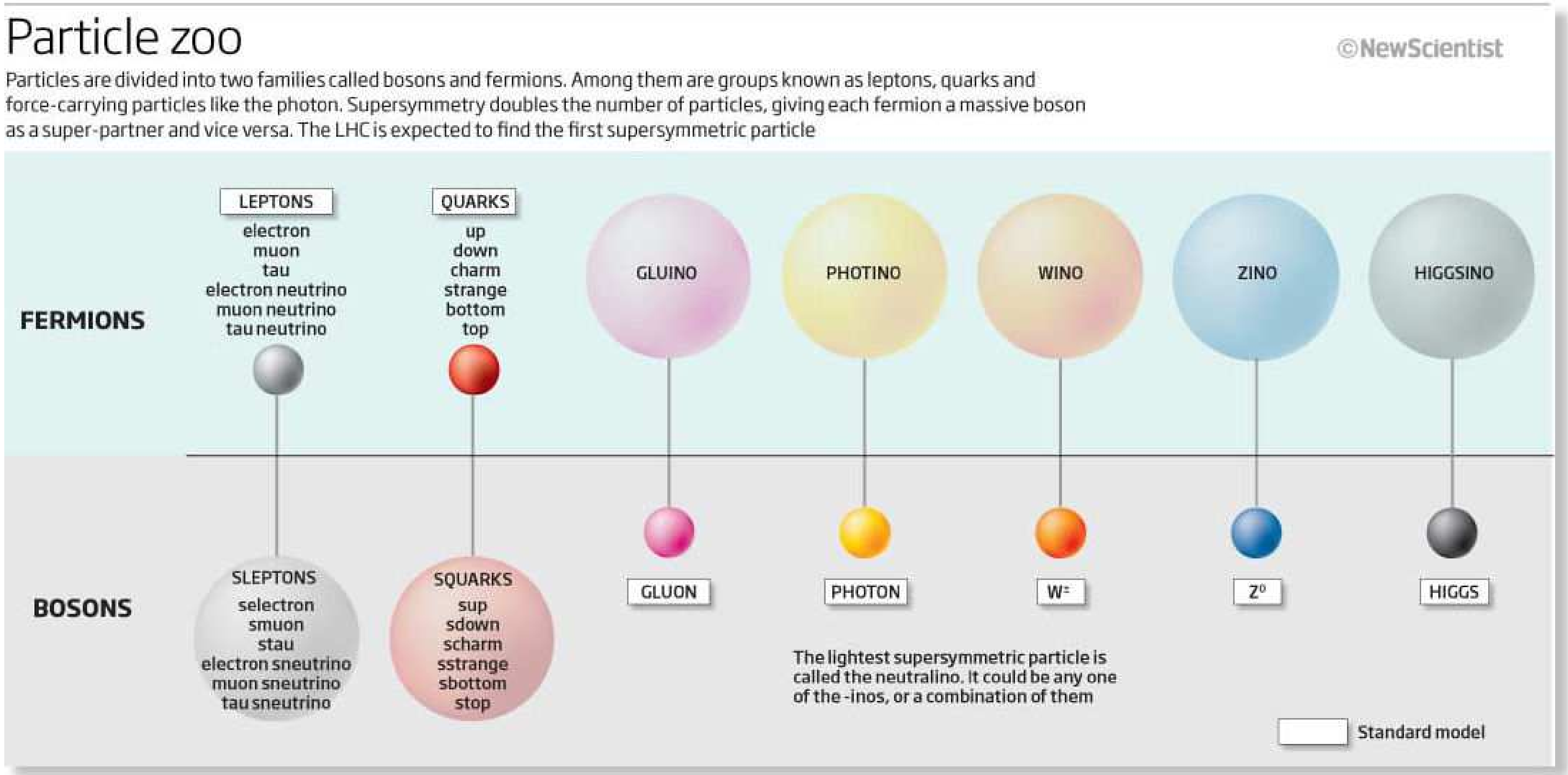



SM is the „**low-energy-limit**“ of a more fundamental theory

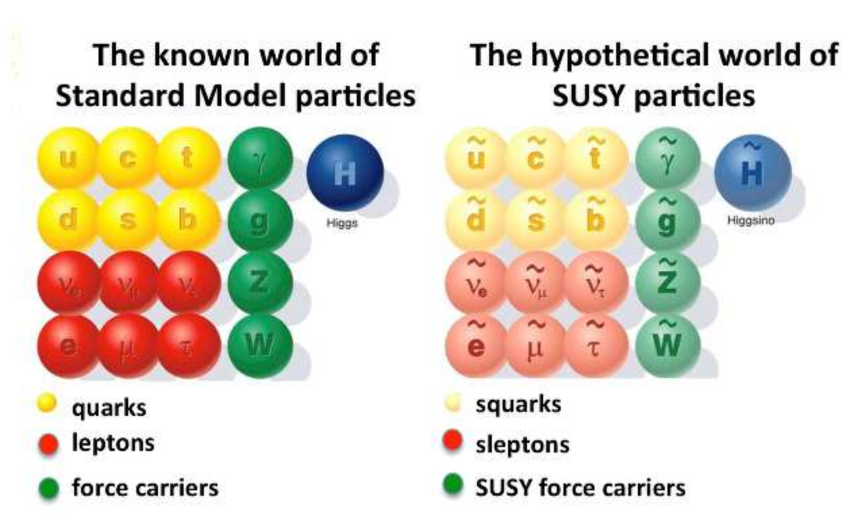
# Introduction – SM Extensions




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

# Introduction – SM Extensions

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

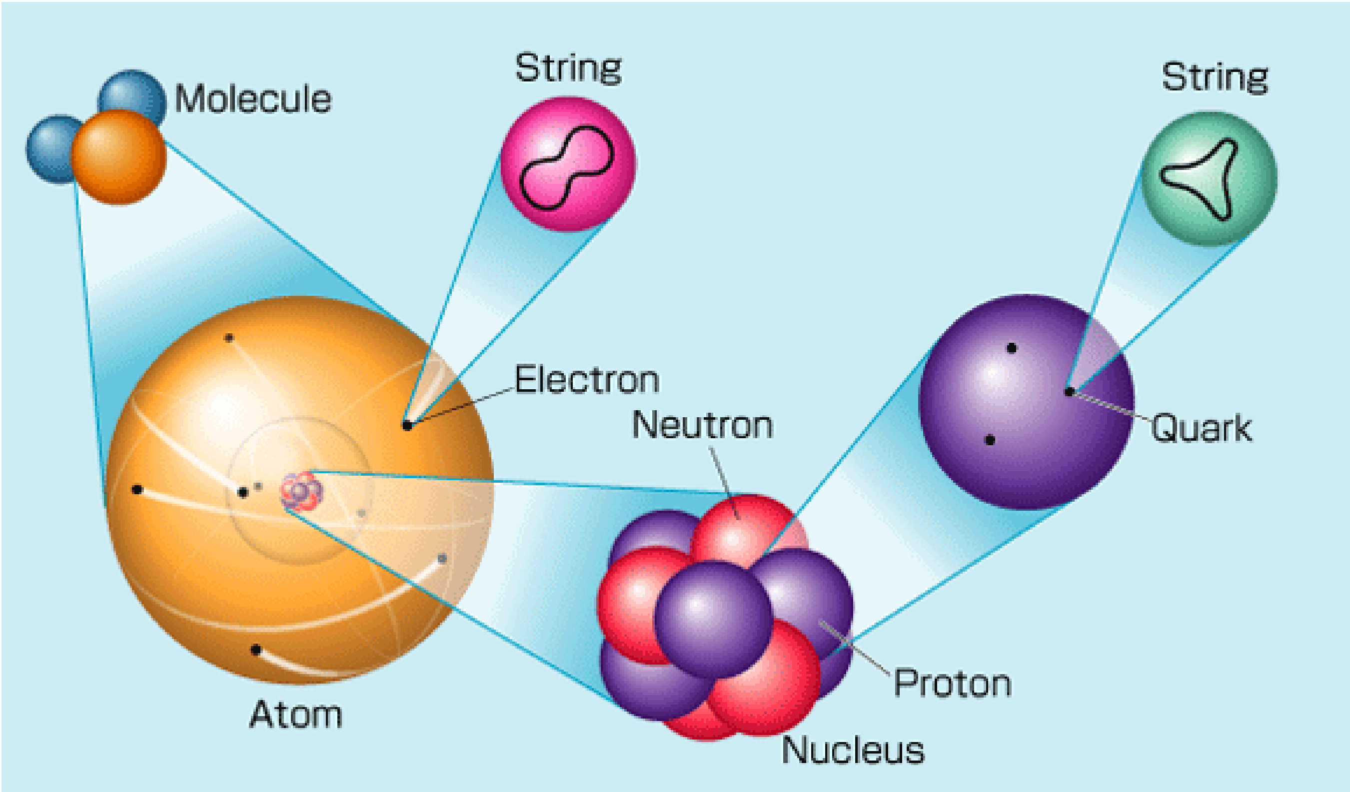



**SUSY'S MID-LIFE CRISIS**

| | |
|---|---|
| 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 |

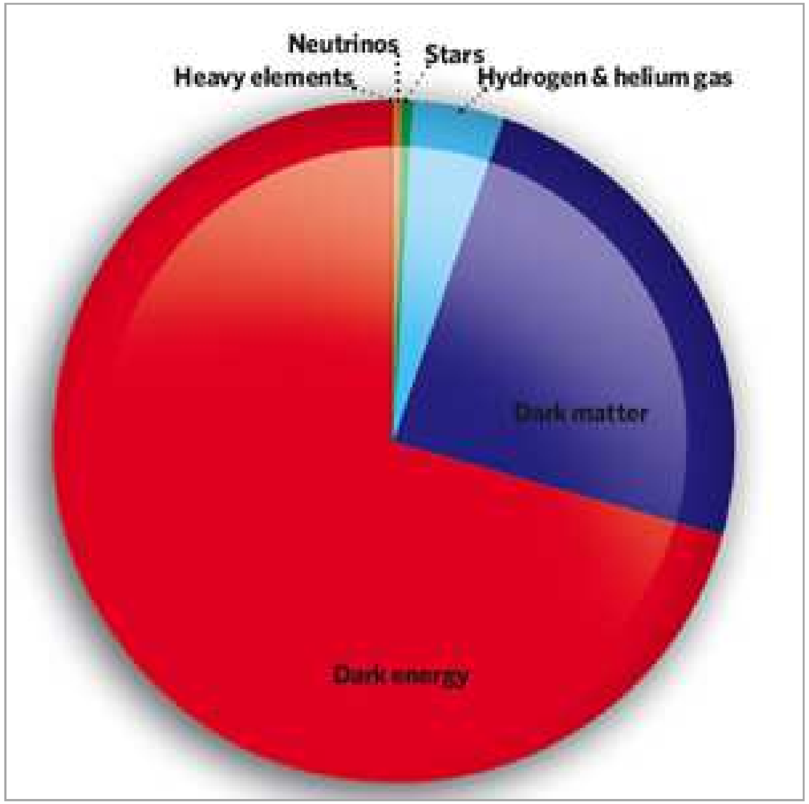
Experiment: **No SUSY particles** (yet)!

# Introduction – SM Extensions




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

# Introduction – More Unknowns



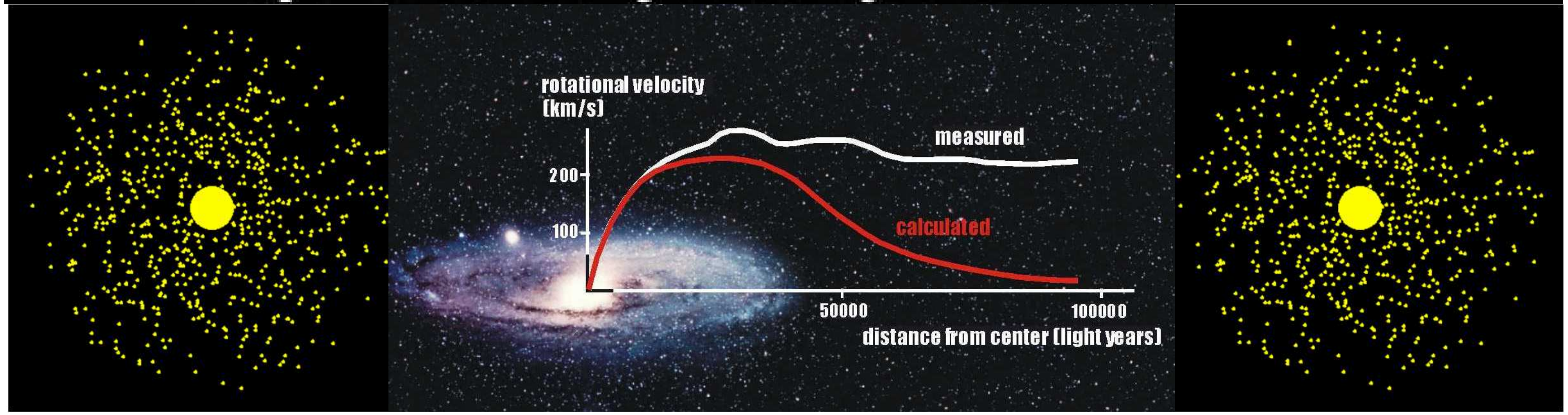

## What we know and what we don´t know

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

# Introduction – More Unknowns

***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

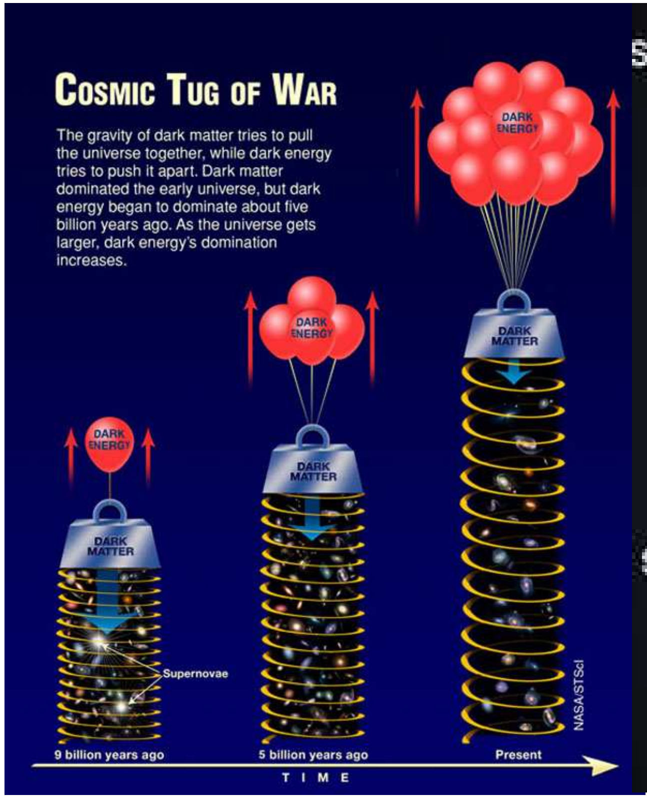
- the motion of stars in galaxies.
- the orbits of galaxies in galaxy clusters.
- the temperature of intracluster gas in galaxy clusters.
- the gravitational lensing of distant galaxies.

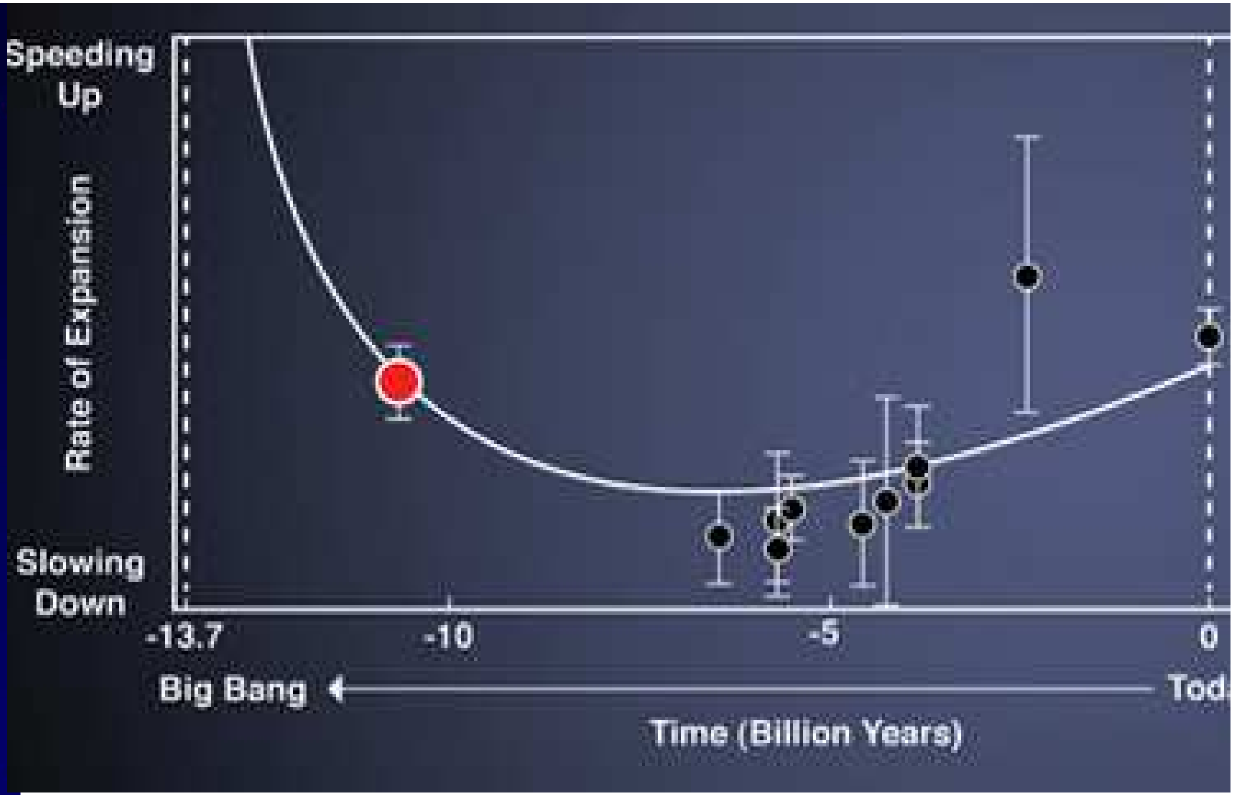



## What we know and what we don´t know

**„Dark Matter“**

# Introduction – More Unknowns

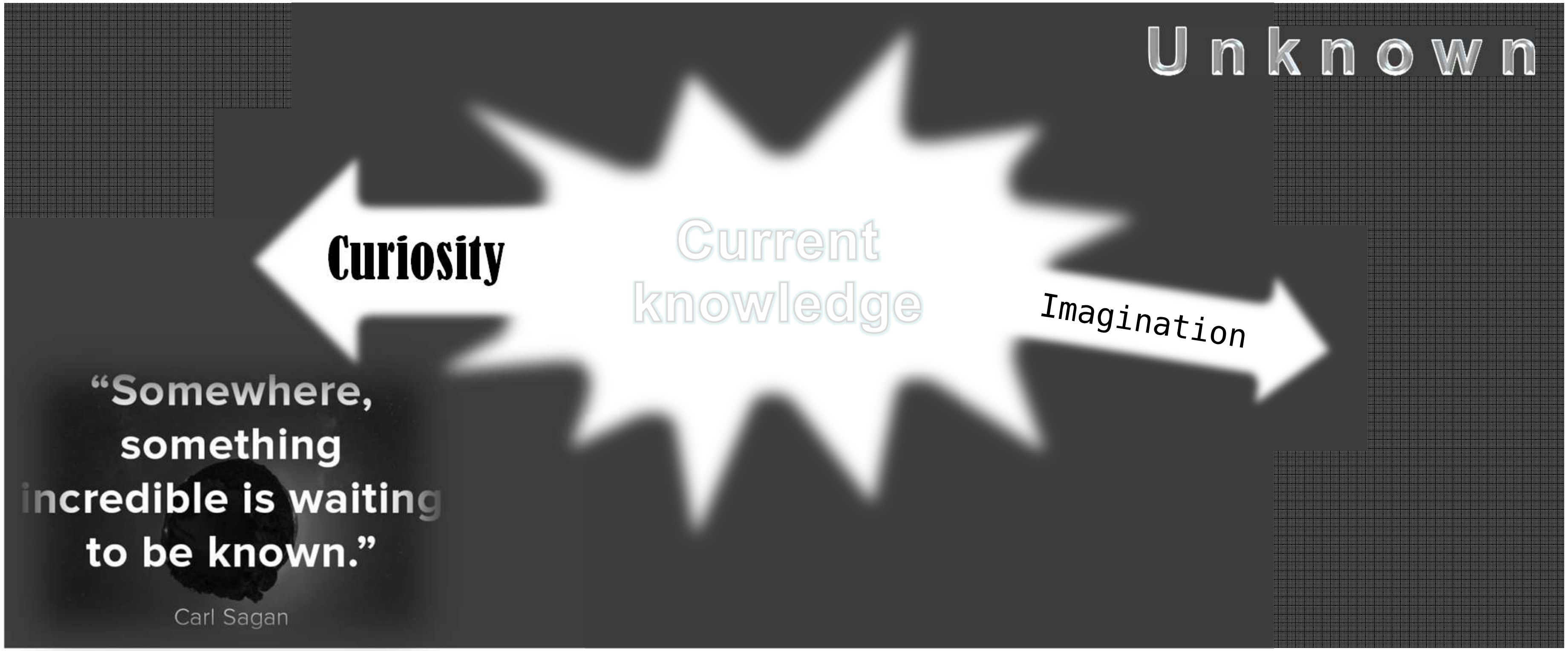



## What we know and what we don´t know

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

# Introduction – Summary, Outlook




**There are things we know that we know; there are things we know that we don´t know, and there are things we don´t know that we don´t know.**
(after D. Rumsfeld)

Science – the endless frontier


გმადლობთ