Developments in Natural Sciences

Symposium of the Royal Society of Sciences at Uppsala
-Tercentenary of the Society-

Kungl. Vetenskaps-Societeten i Uppsala

Prof. Karl Jakobs
Physikalisches Institut

Universität Freiburg / Germany

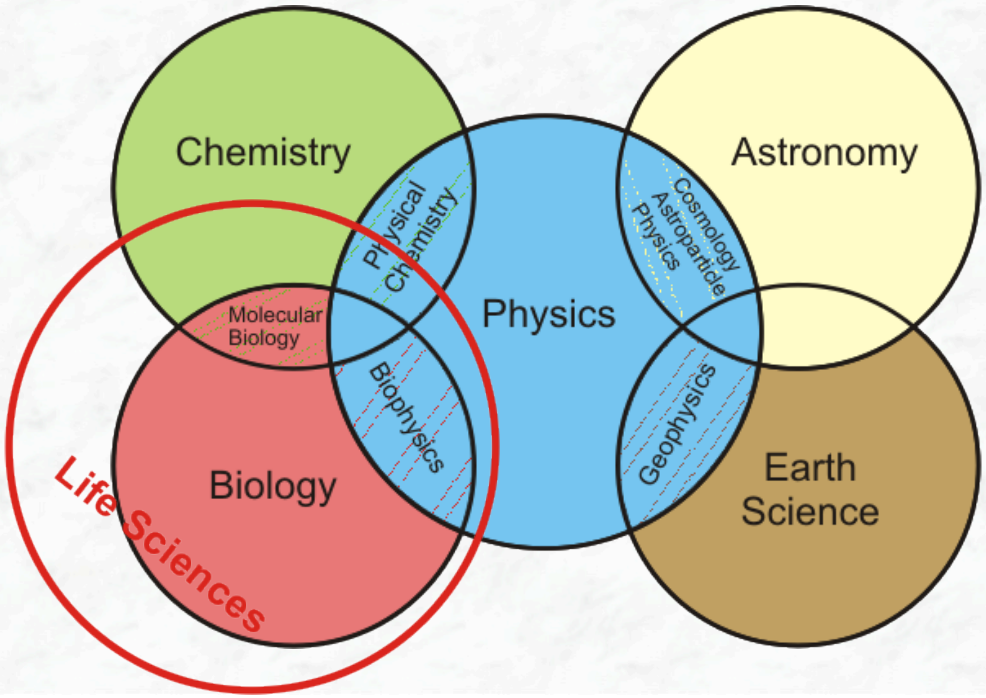
Ancient Greek: φύσις (physis) = "nature"

- In ancient and medieval times the study of Nature was known as ***Natural Philosophy***

- Modern Natural Science emerged in the Age of Enlightenment: ***Scientific Revolution***

  Philosophical interpretation of Nature was replaced by a scientific approach

- Natural Science has diversified into many branches*:*

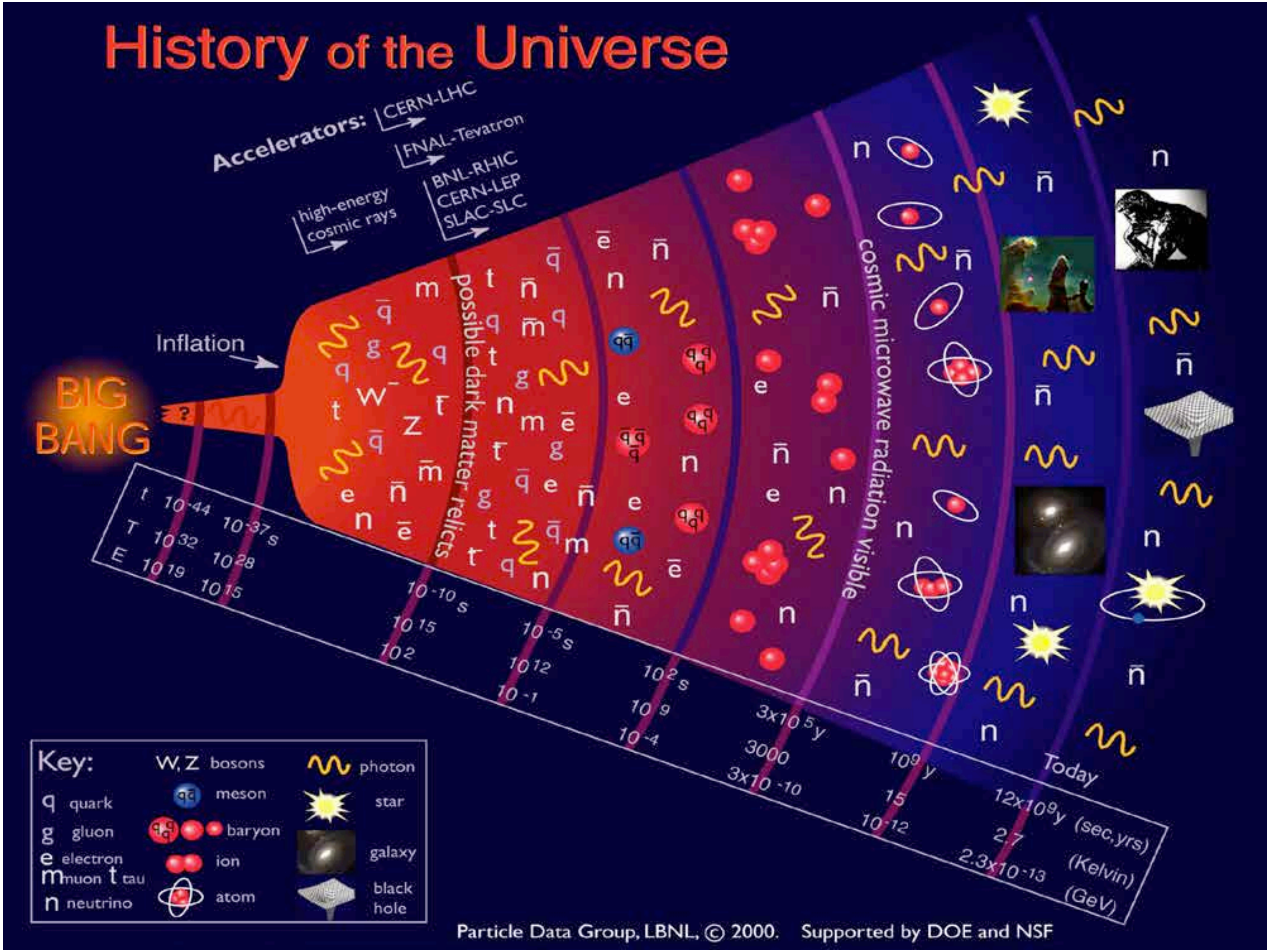


Objective of Physical Sciences

• Unified and all-embracing description of matter and forces (interactions)

- from smallest distances: 10^{-18} m (today)
- to cosmological scales: 10^{25} m

• Fundamental questions:
- What is matter made of?
- Are there fundamental building blocks?
- If yes: what forces act between them?


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10-1
10 2 s
10 9
10-4
3x10 5 y
3000
3x10-10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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Methodology of Natural Science

- **Experiments** *("A question to Nature")*
  Experimental measurements → precision, objectivity, reproducibility,…

- **Theory → predictive power ("Laws of Nature")**
  - Use of **Mathematics** *("The language of Nature")*
  - Exploit **Symmetries**, aim for unifying principles

Emmy Noether (1882–1935)

- New / better measurements may lead to **paradigm changes** !
  - Concepts may be wrong and require drastic changes.
  - However, "old theories" may be contained as border cases in the new theories
  - Theories may be falsified (Karl Popper)

The early phase of Natural Sciences

Sir IsaacNewton
(1643 - 1727)

- Laws of motion (classical mechanics)
  (Standard Model of mechanics until 20^{th} century)

- Theory of gravitation, unifying principle

- Periodic system of chemical elements (reduction)

- Unified theory of electric and magnetic phenomena
  (electromagnetic force, prediction of electromagnetic waves)

$$\mathrm{div}\mathbf{B} = 0, \qquad \mathrm{rot}\mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0\,,$$

$$\mathrm{div}\mathbf{E} = \frac{\rho}{\varepsilon_0}, \quad \mathrm{rot}\mathbf{B} - \mu_0\,\varepsilon_0\,\frac{\partial \mathbf{E}}{\partial t} = \mu_0\,\mathbf{j}.$$

- Numerous innovations and applications (still ongoing…)

J. C. Maxwell
(1831 - 1879)

Electricity, radio, television, communication systems, transistors, microelectronics,….

Impact of Natural Sciences

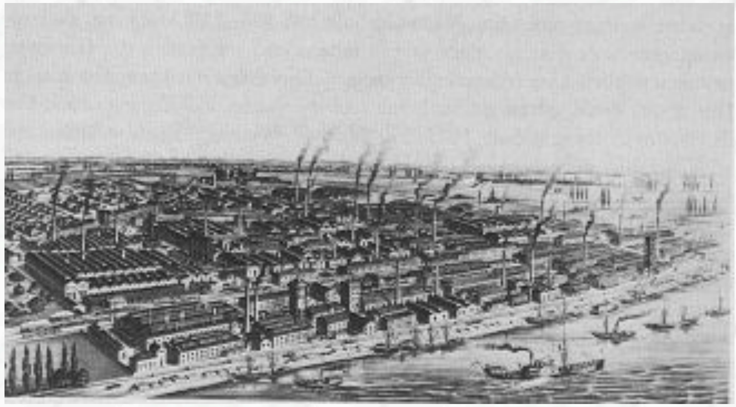
- *Advances in Natural Sciences translated into new technologies that dramatically changed our life and society:*

  (i) Development of chemical industry (19^{th} century)

  - Large scale production of:
    Sulphuric acid, sodium carbonate, dyestuffs, fertilizer,…

  - Pharmaceutical products:
    Acetylsalicylic acid, ….,penicillin

  - Synthetic materials
    (the material of the 20^{th} century)



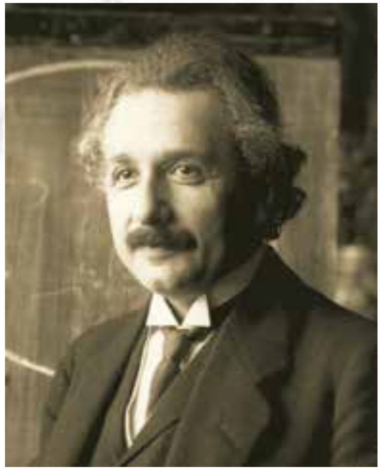
Badische Anilin- und Soda-Fabrik (1893)

  (ii) Development of automotive industry
  (steam engines → thermodynamics → automotive industry)

- *New concepts resonate with other sciences (e.g. mathematics and philosophy)*

20^{th} century paradigm changes

- ***Quantum Theory***
- ***Theory of Relativity***



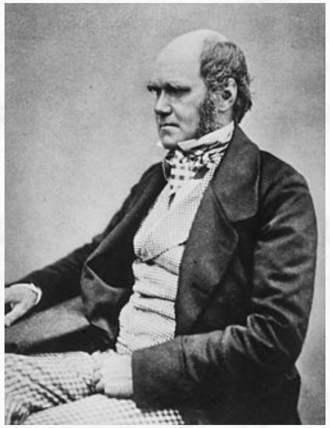
- Uncertainty principle

  $$\Delta x \cdot \Delta p \geq \hbar$$

- Probabilistic interpretation
- Matter-wave dualism
- Antimatter
  (doubles the number of particles)

- Matter and energy determine space and time
  (radical change of concept)
- Energy – matter equivalence

  $$E = mc^2$$



C. Darwin (1809 – 1882)

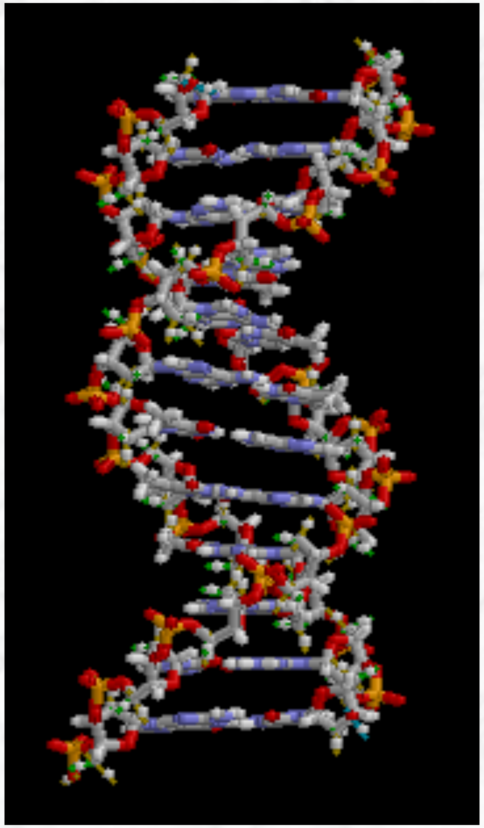
- ***Darwin's evolutionary theory***

- ***Discovery of the structure of DNA***

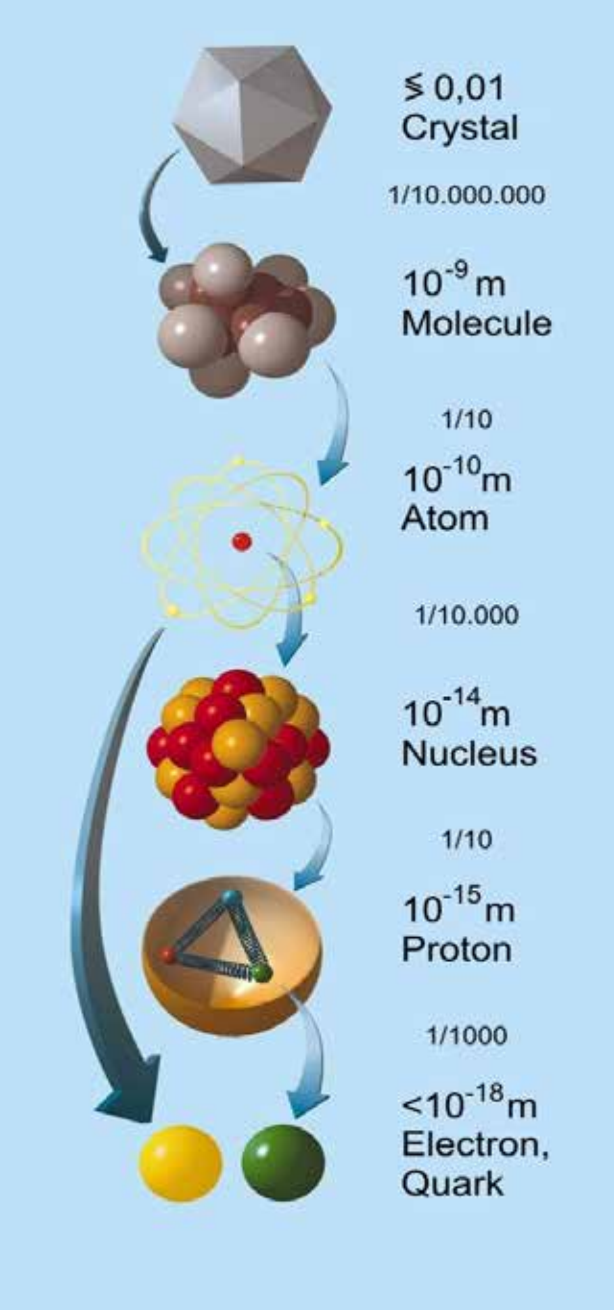
(Deoxyribonucleic acid that contains the genetic instructions used in the development and functioning of all living organisms)

The basis of modern genetics

F. Crick (1916 – 2004)
J. Watson (1928 -)



Exploring the interior of matter

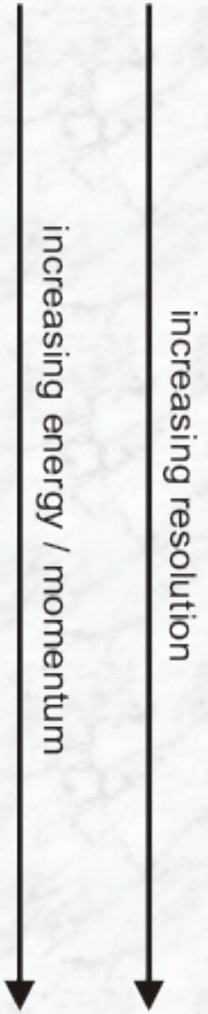


eye, microscope
(light)

electron microscope
(electrons)

particle accelerators
(synchrotron radiation)

particle accelerators
(high energy particles)

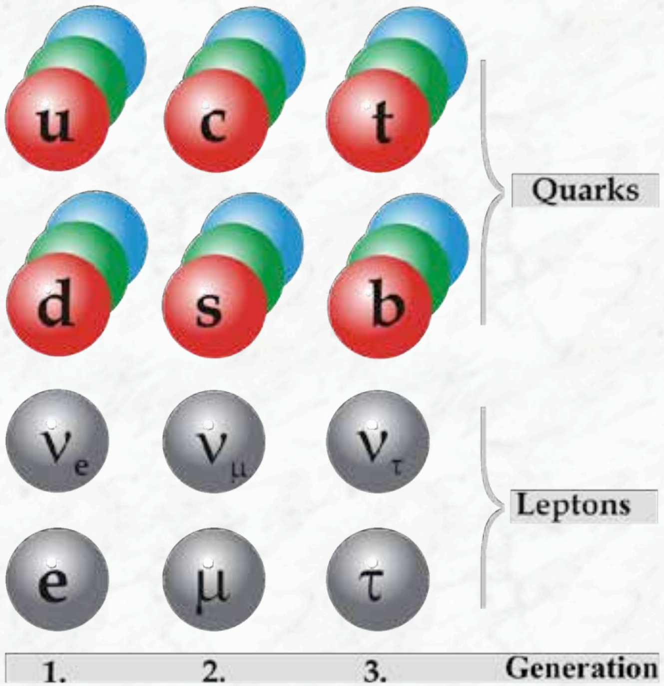


$$\Delta x \propto \frac{1}{p}$$

New mass states accessible: $E = mc^2$

Today's "Standard Model" of Particle Physics

1. Building blocks of matter: Quarks and Leptons

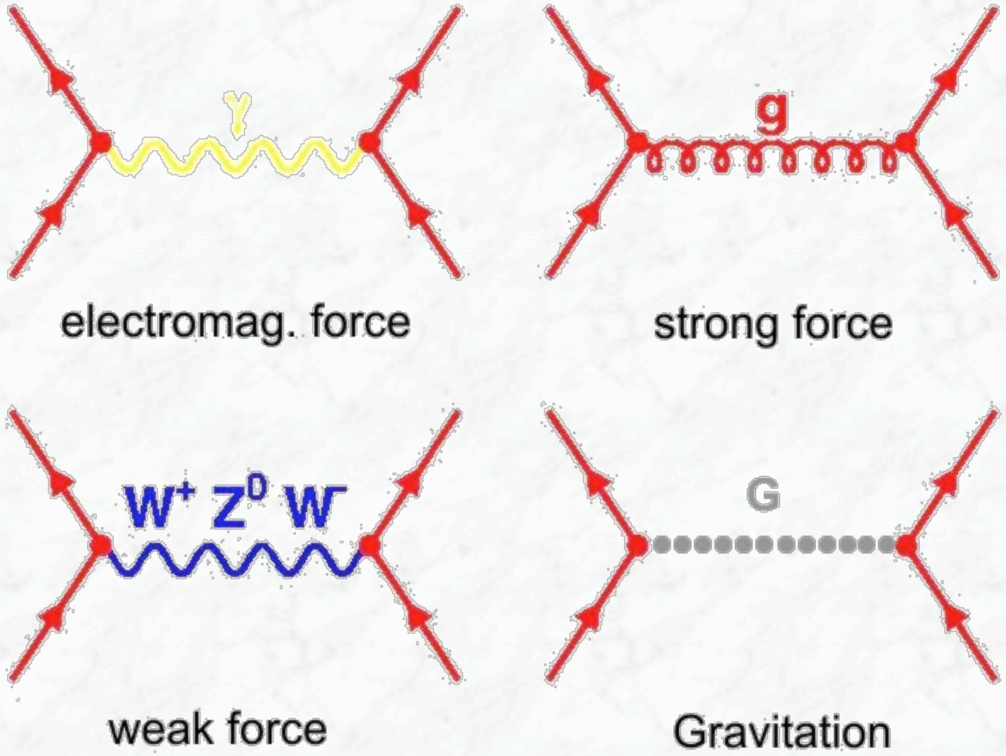


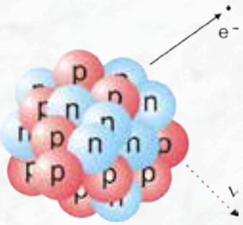
- Mass that surrounds us is built up of 1st generation particles, e.g. proton = (u,u,d)

- Heavier copies in 2nd and 3rd generations, $m_t \approx 200\ m_{proton}$

- Quarks and leptons appear "point-like", down to 10^{-18} m

2. Fundamental forces



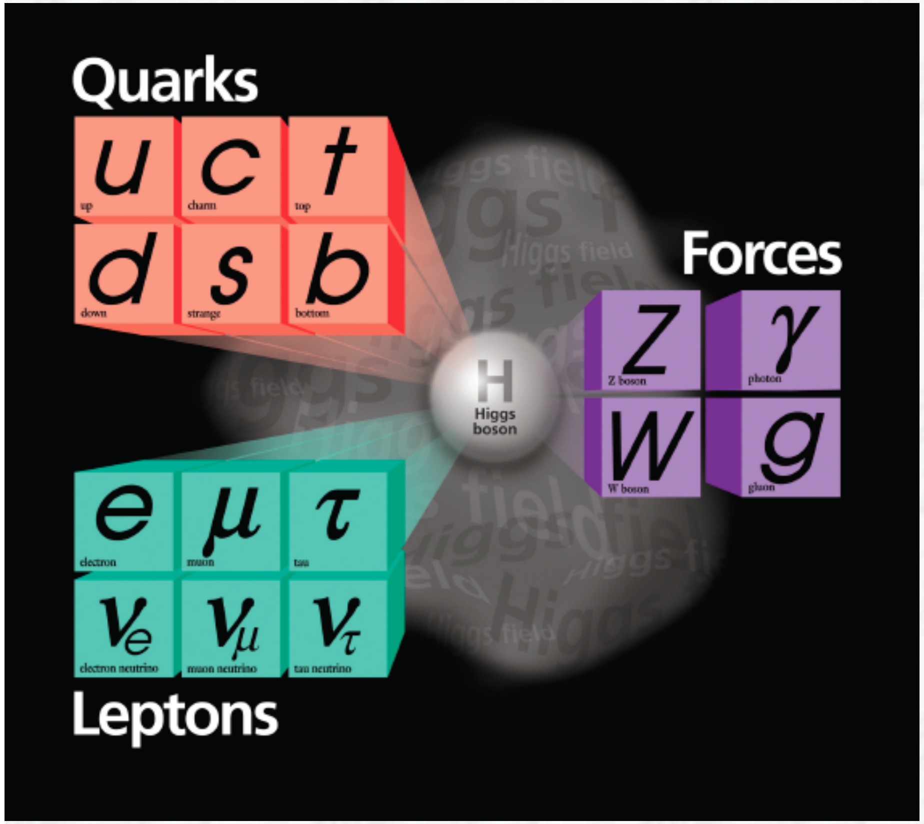


β decay

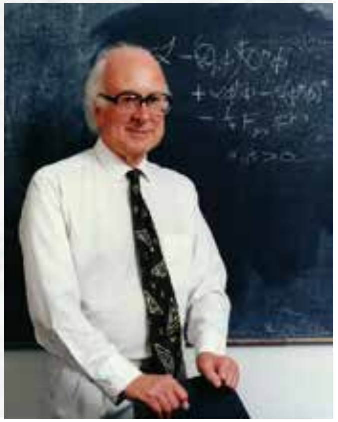
Mediator particles: **Photon (γ), Gluons (g), W and Z bosons**
(in the picture of quantum field theories: interaction via exchange of these particles)

- Photon and gluons are mass-less, M_W = 80.4 GeV, M_Z = 91.2 GeV
- Force carrier particle of gravitation (graviton) not yet discovered

The Problem of Mass

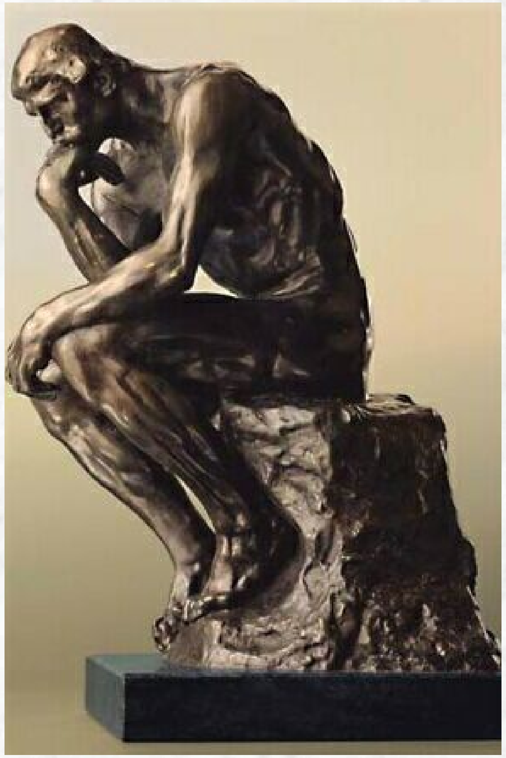


- Theoretical description
  → mass-less particles
- To generate mass: a new particle field (Higgs field) is postulated, penetrates vacuum
- Mass via interaction of particles with the Higgs field
- <u>Prediction</u>: Higgs particle
  $100 < m_H < 1000$ GeV/c^2



proposed by P. Higgs (Univ. Edinburgh)
[Theory: 1964, P. Higgs, R. Brout und F. Englert]

The Open Questions



Open Questions

1. **Mass**

   What is the origin of mass?

2. **Unification**

   - What is the fundamental underlying theory?
   - How can gravity be incorporated?
   - Are there new types of matter?

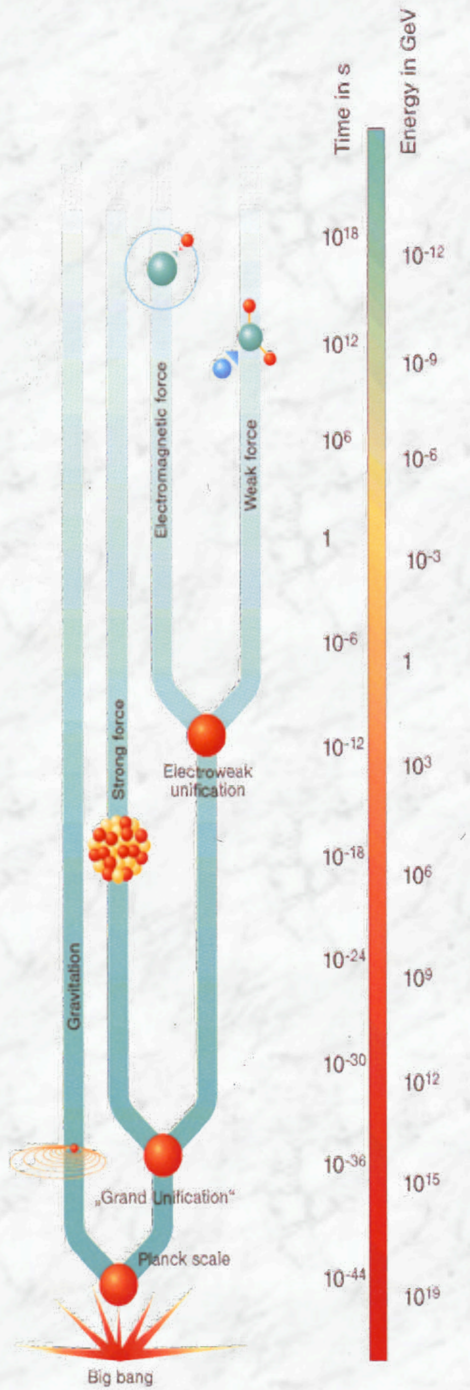
   What is the Dark Matter in the Universe made of?

3. **Matter-antimatter asymmetry**

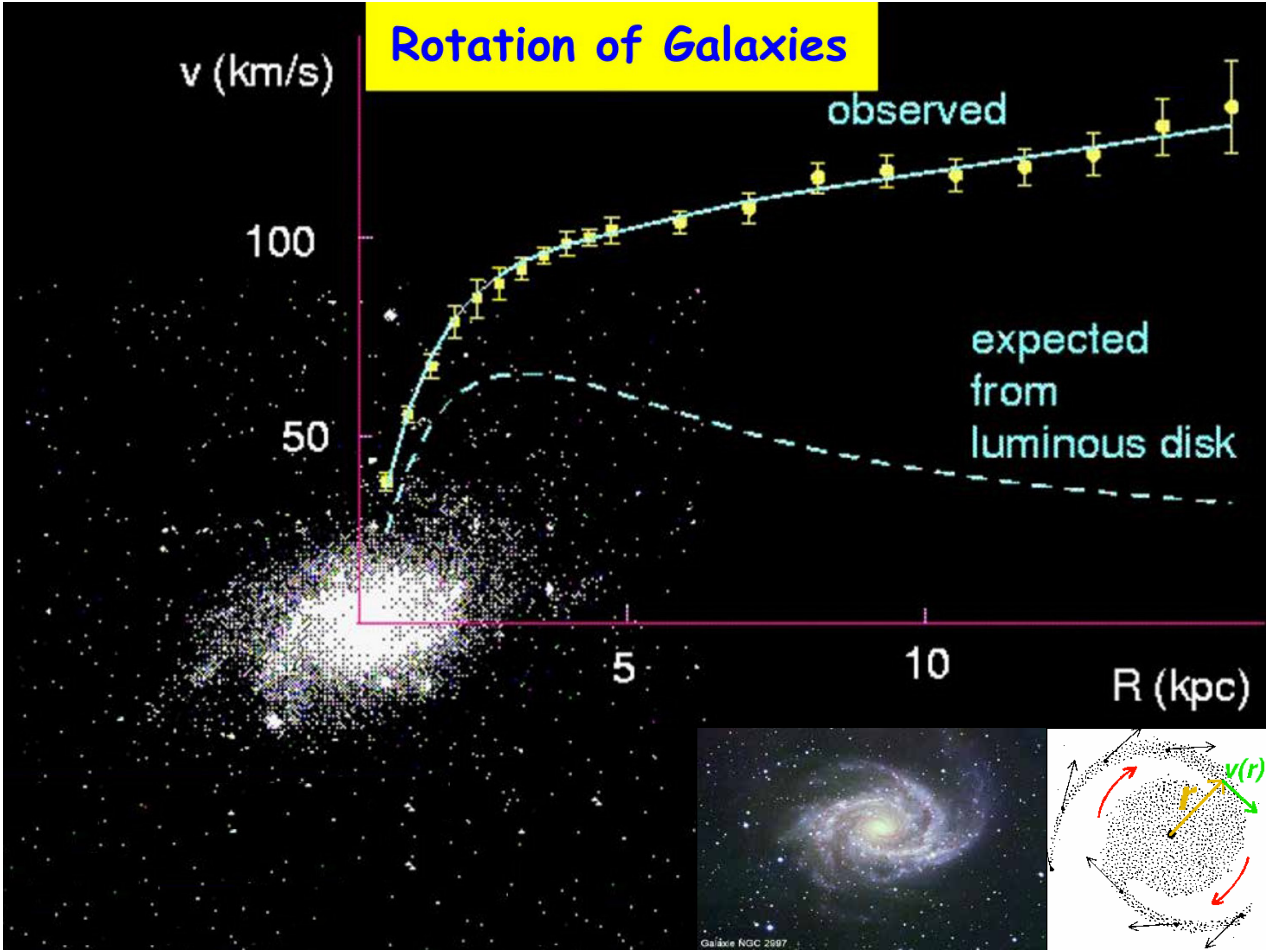
   … or why do we exist?

4. **Are there extra dimensions in space?**

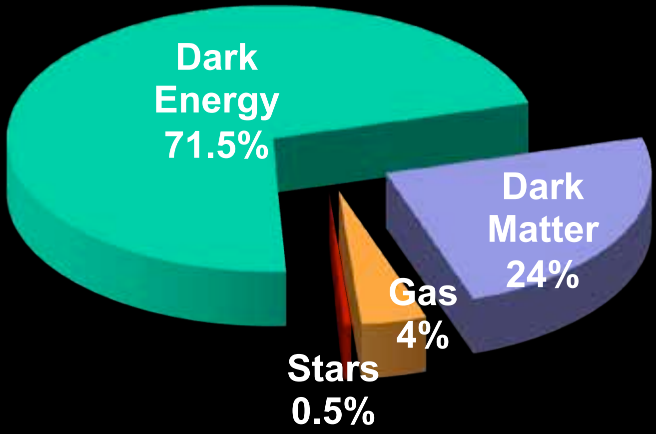
   … or why is gravity so weak?

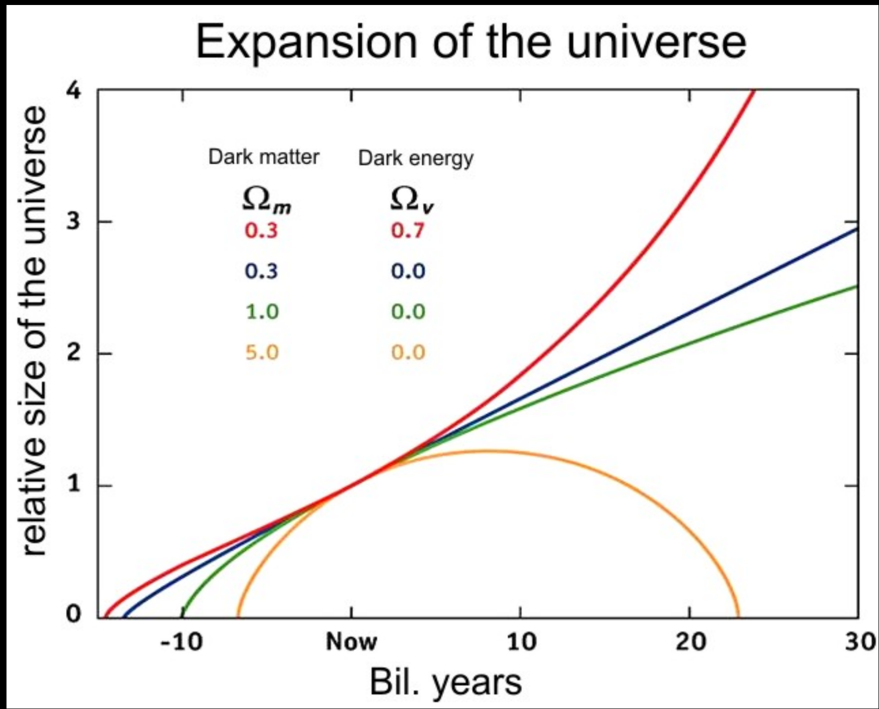


Rotation of Galaxies



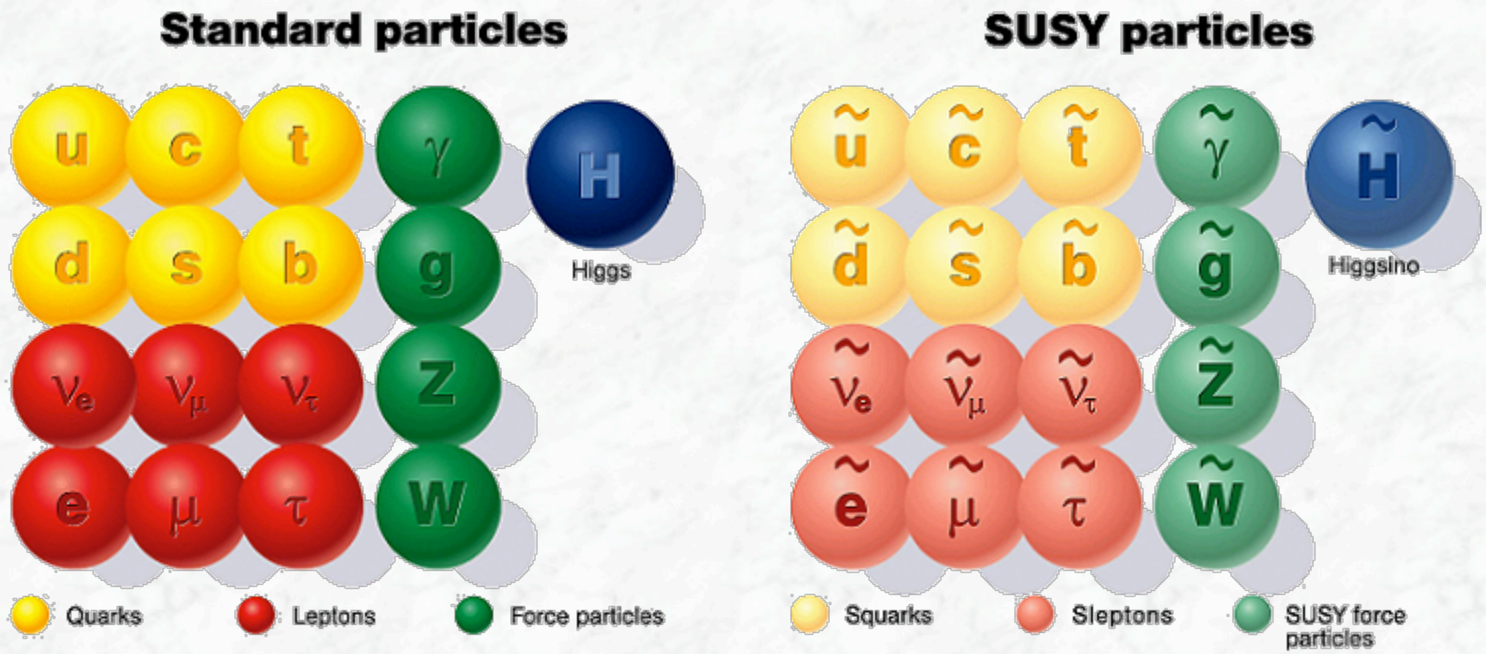
Energy in the Universe





A prominent idea to explain Dark Matter: Supersymmetry

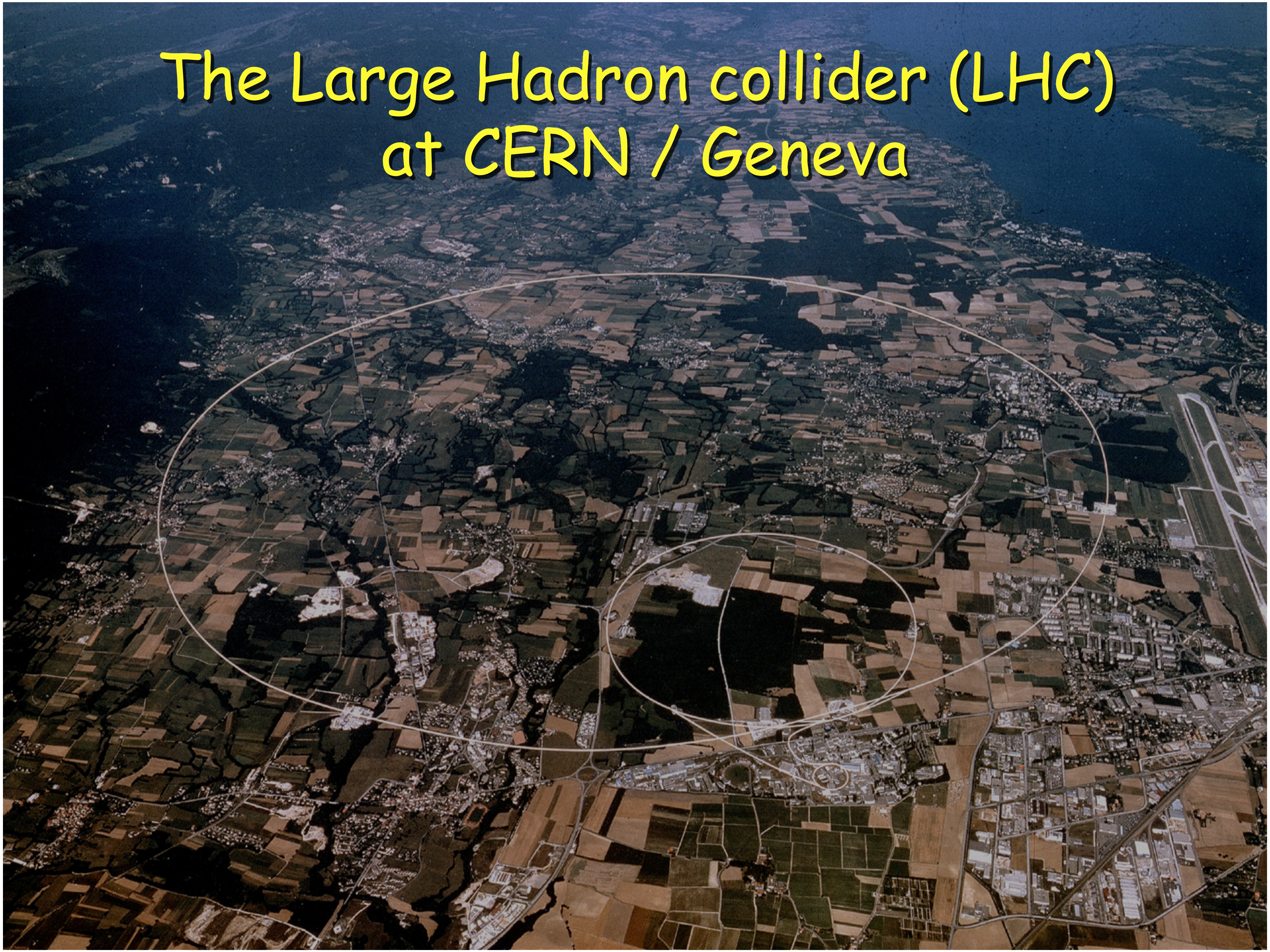
-symmetry between matter particles and force mediators-



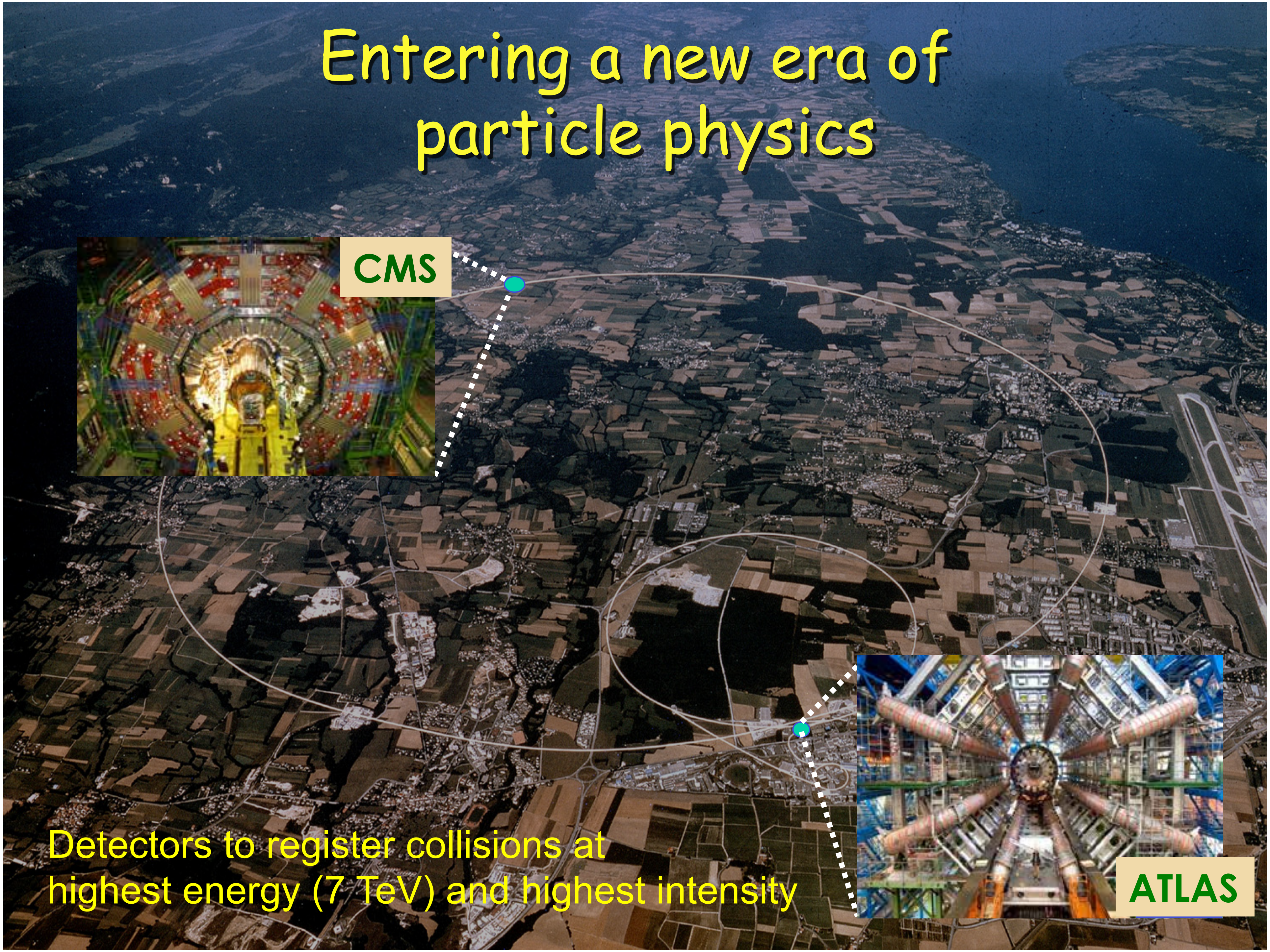
- Partner particles introduced for all known particles
  Supersymmetric particles must be heavy (not seen yet)

- The lightest supersymmetric particle is stable and interacts only weakly
  → candidate for Dark Matter, relic density from big bang

The Large Hadron collider (LHC) at CERN / Geneva

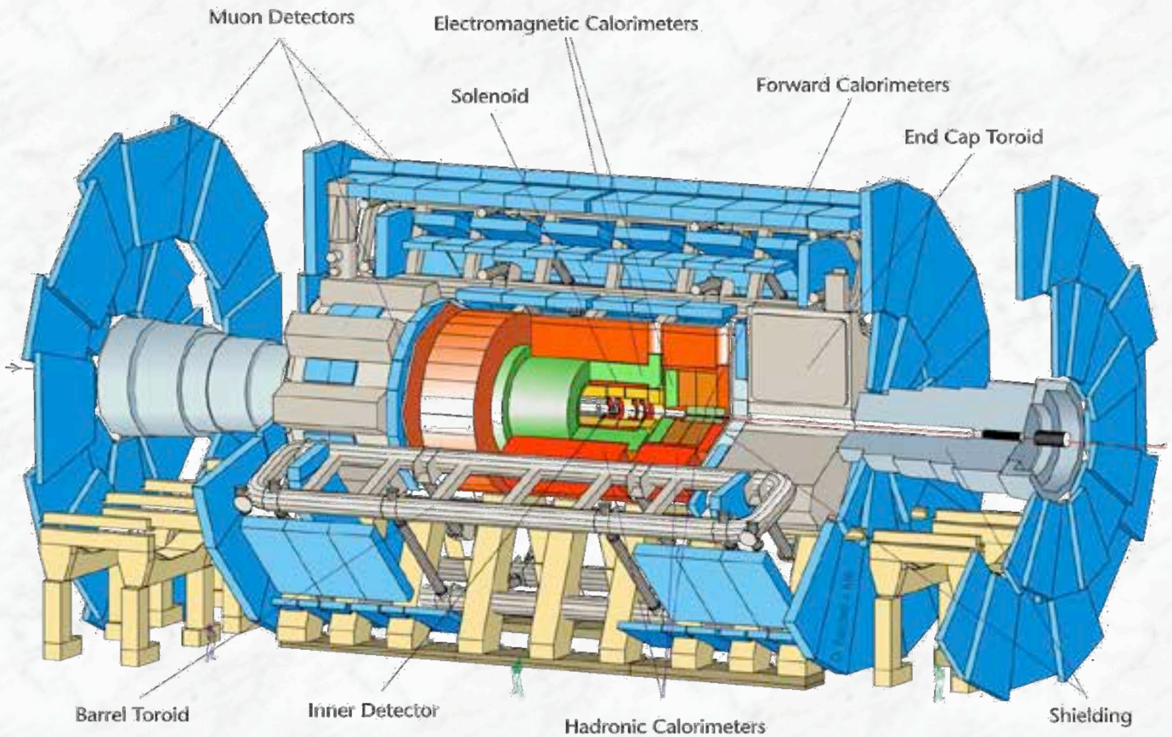


Entering a new era of particle physics



Detectors to register collisions at highest energy (7 TeV) and highest intensity

The ATLAS Experiment

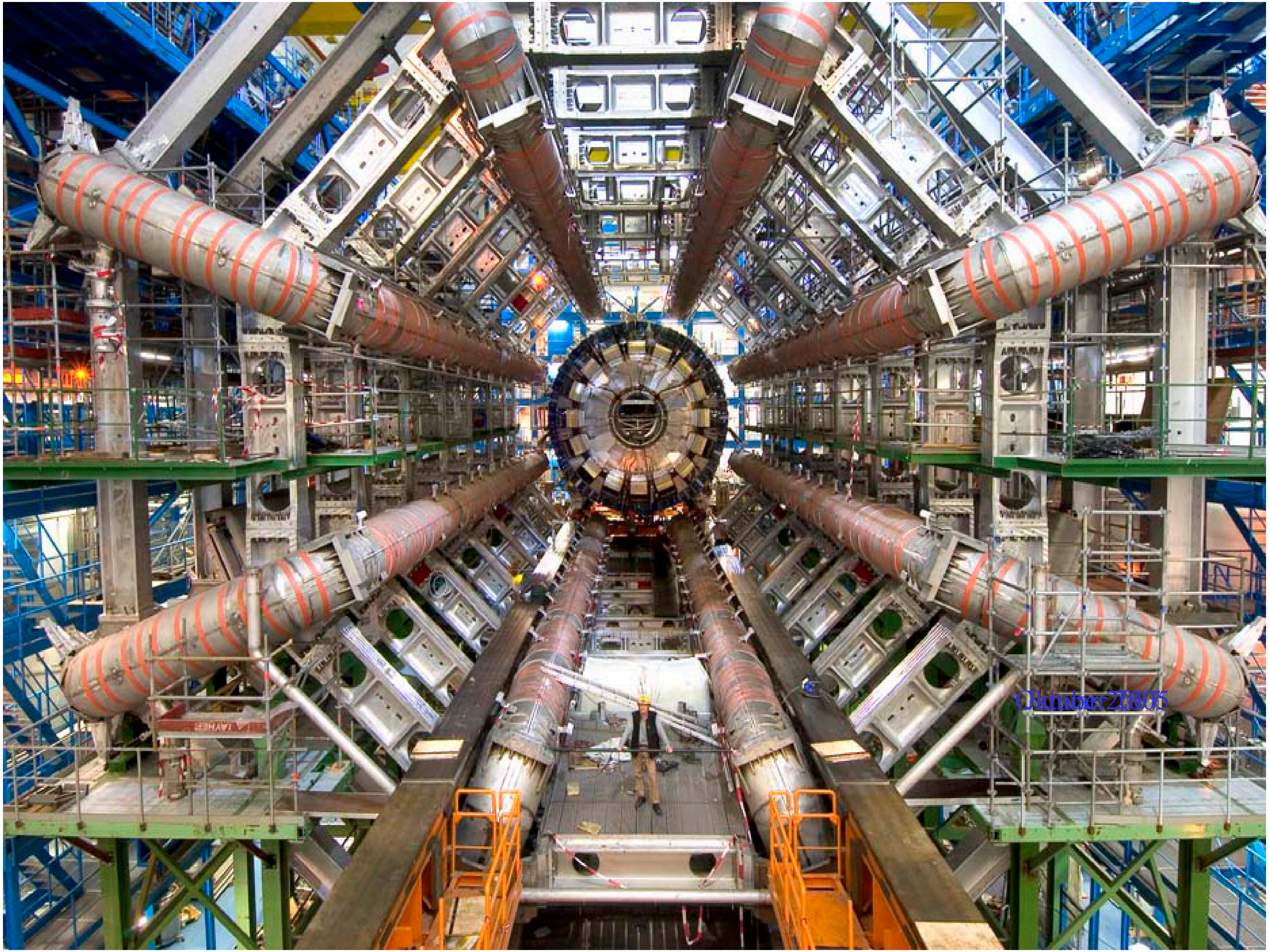


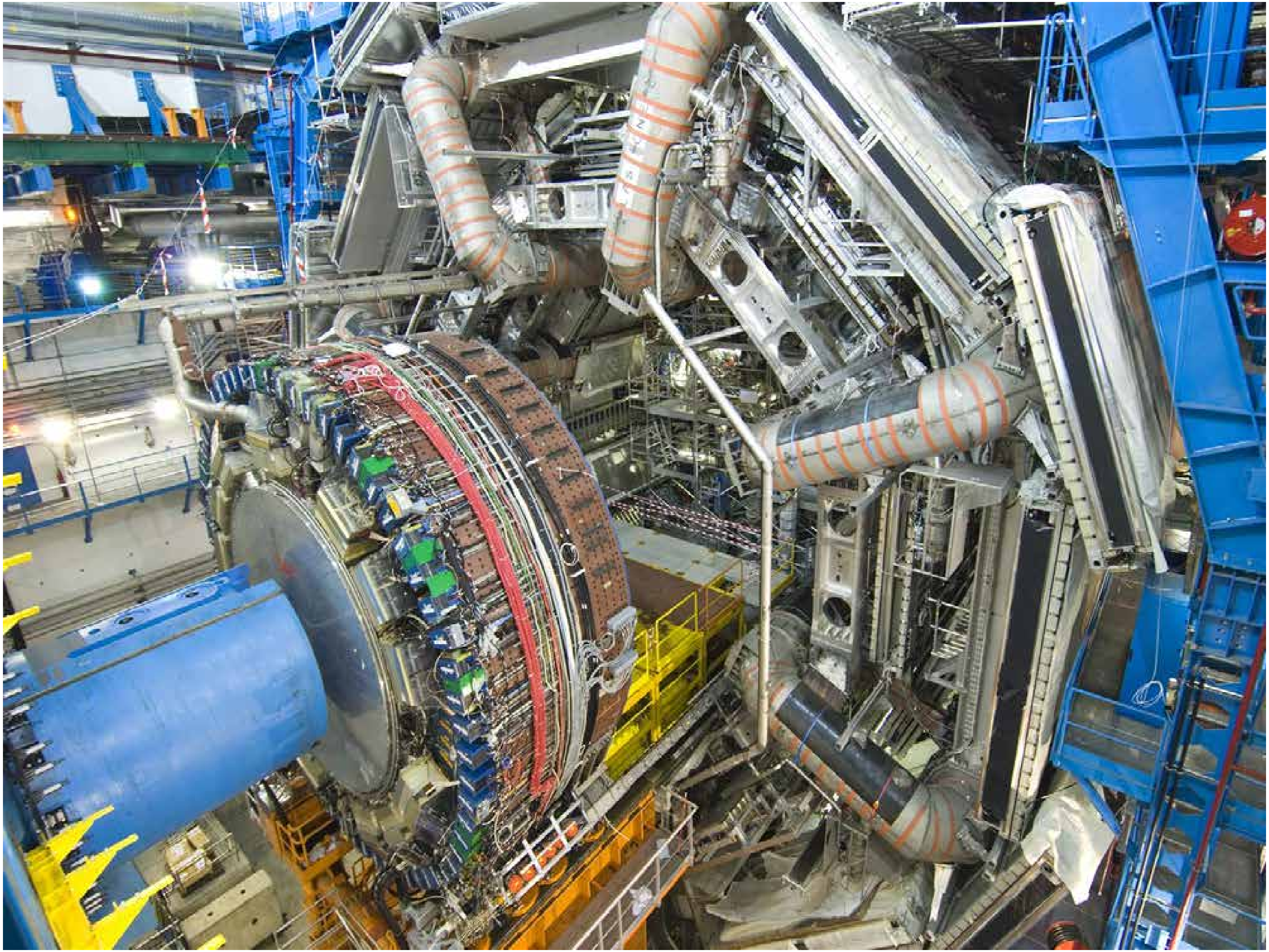
Diameter 25 m
Total length: 46 m

- 40 Mio. collisions / sec (every 25 ns)
- Several hundred particles per collision
- Electronic information from about 100 Mio independent channels
- High precision measurements (e.g. space coordinates of particles with a precision of 15 μm)
- Front-line technology: detectors, precision, electronics, computing, …

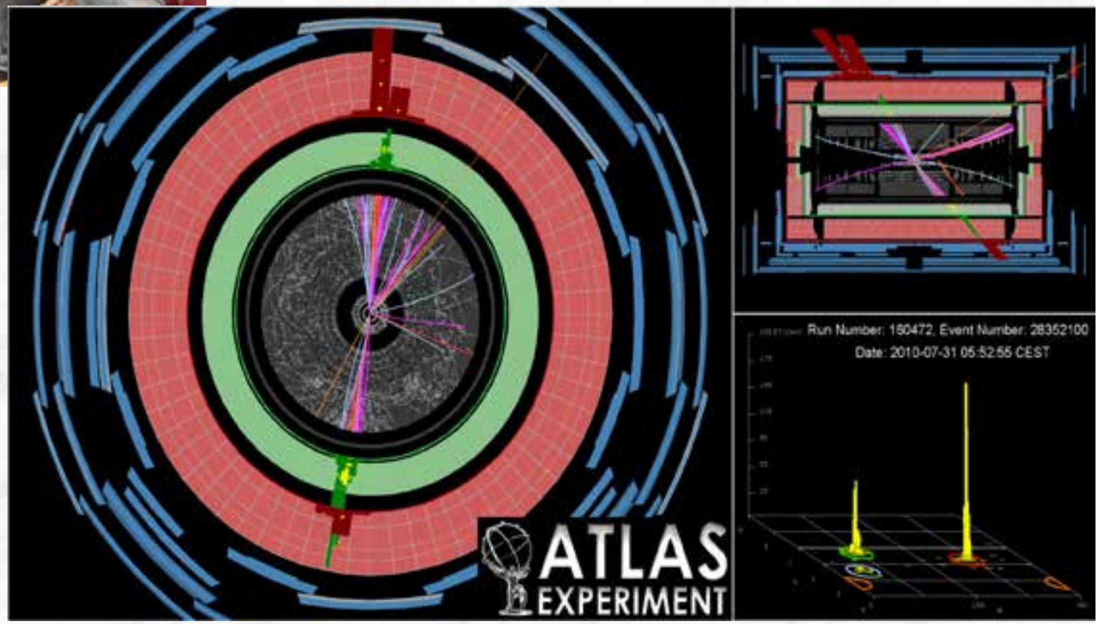
170 collaborating institutes (37 countries)
2500 Physicists

..,Lund,.....,Stockholm,
....,***Uppsala***,...





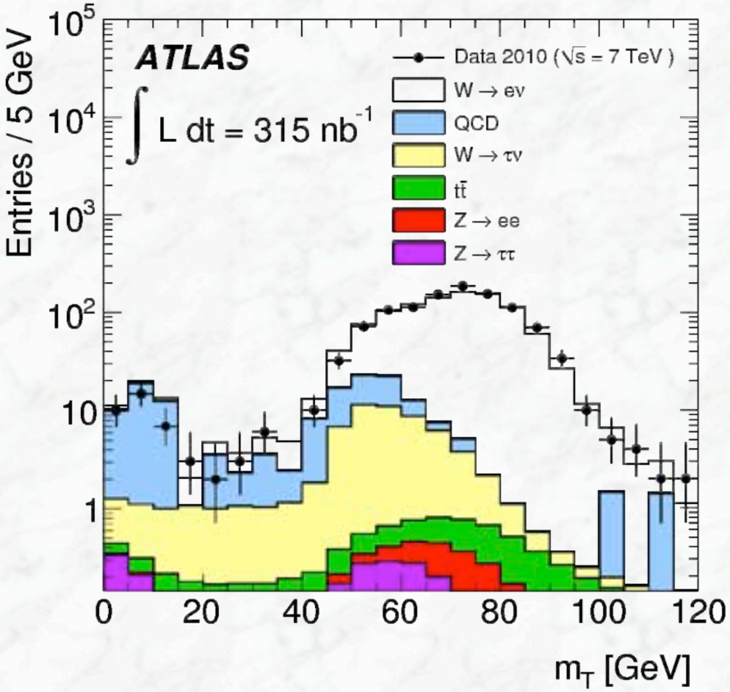
Since 30. March 2010: Collisions at 7 TeV



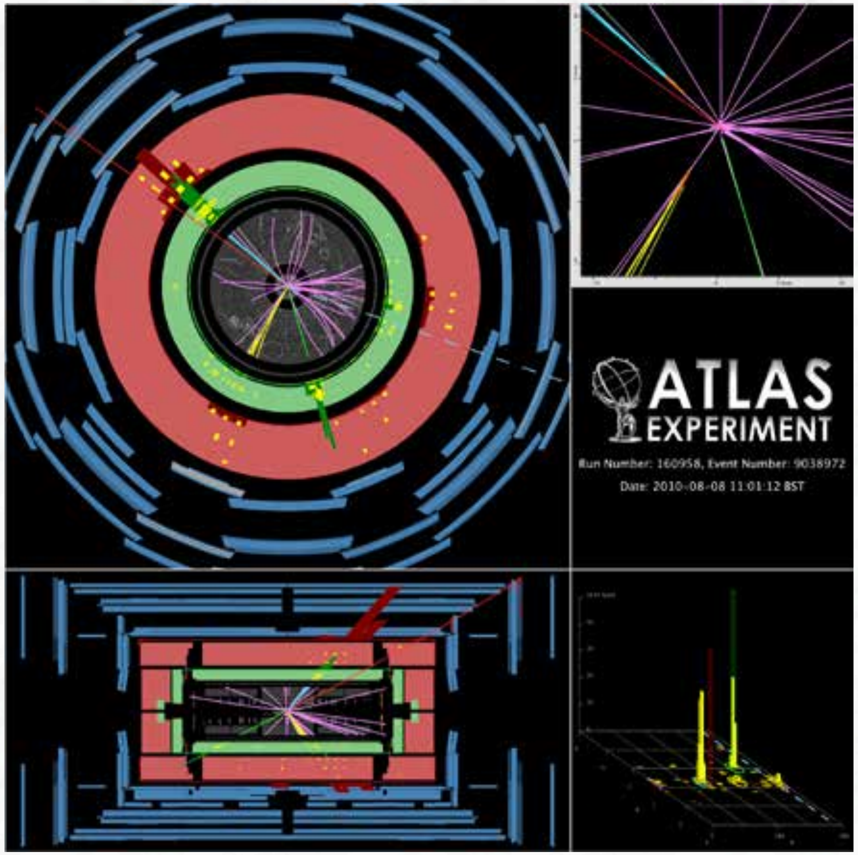
… highest accelerator energy ever reached

Re-discovery of W, Z particles and of the top Quark

- all known particles seen after only a few months of operation-



~ 1000 W → eν decays

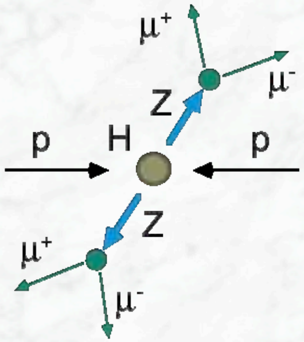


A candidate for tt → Wb Wb → eνb μνb

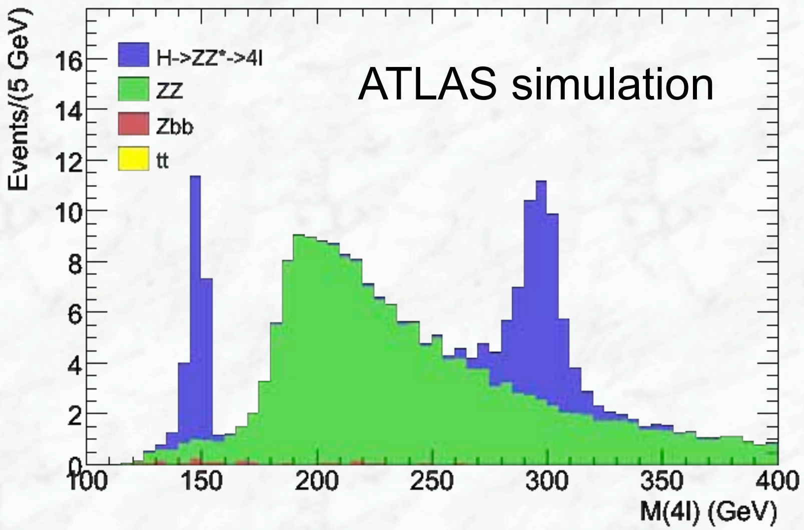
- First measurements of W/Z and top production properties published;
- Important benchmark processes in the search for new physics

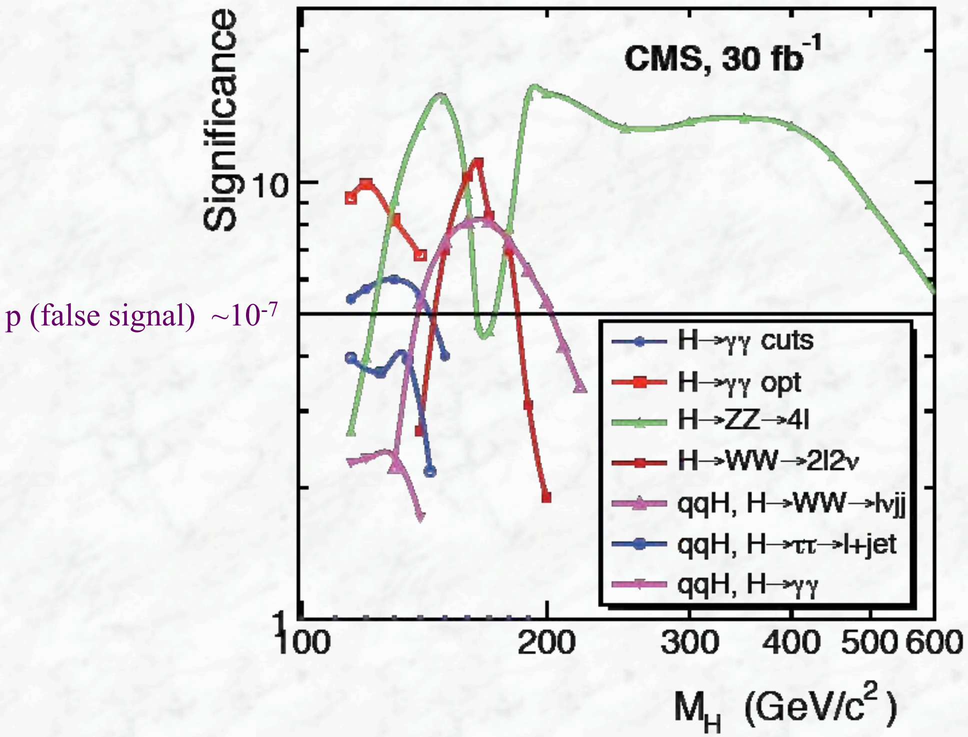
The Search for the Higgs particle

- **H → Z Z → ℓℓℓℓ**
  (the „golden decay mode")



Several different decay modes can be searched for
→ expected discovery significance





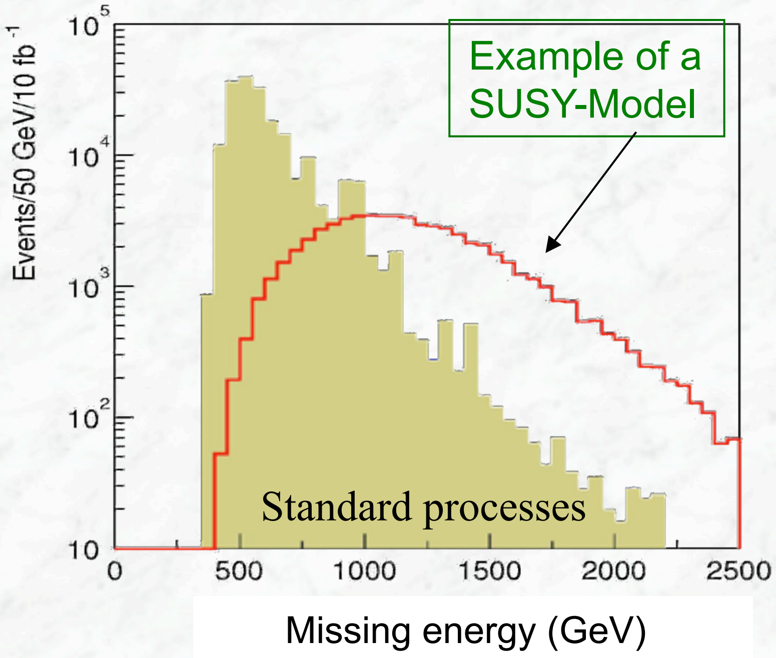
Signals of a Higgs particle might show up after a few years of running

If the Higgs particle exists,
it will be discovered at the LHC

The Search for the Dark Matter particle

- The supersymmetric partners of quarks and gluons are expected to be produced with high rates
- They decay into the lightest SUSY particle (LSP)
- Weakly interacting → leaves the detector, carries away momentum and energy

  → characteristic signature: missing energy



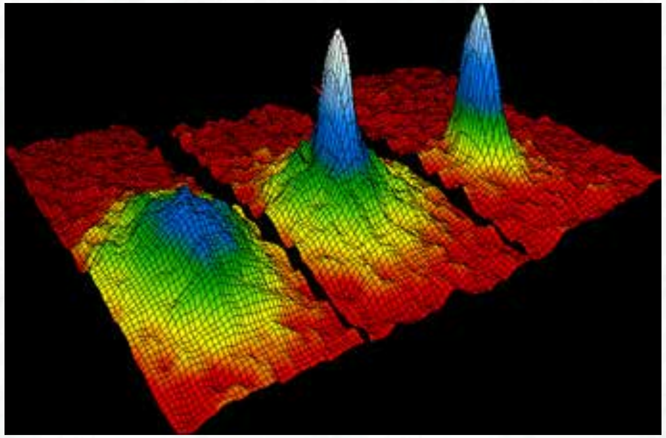
"If supersymmetric particles with masses up to ~ 3 TeV exist, they can be detected at the LHC"

Properties → predictions for the dark matter density in the universe

Comparison to astrophysical measurements

....other highlights / important research topics

I. Quantum effects and applications

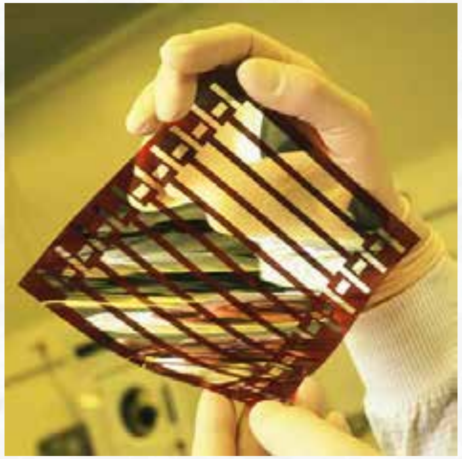


- Bose-Einstein condensation
  (new phase of matter, quantum effects
  become apparent at a macroscopic scale)

- Quantum information, teleportation,
  cryptography,....

- Quantum effects in life science ?

II. The energy question



- Chemistry of energy conversion / storage
  (beyond oil and gas: methanol economy?)
- Battery technologies
- Solar cells, organic solar cells, fuel cells
- ….

III. New materials, material science

Design and development of new materials with application
specific properties

Summary

- Natural Sciences have advanced our knowledge enormously over the past centuries and have significantly shaped life and society and will continue to do so.

- There were fascinating questions in the past, there are fascinating questions today:

  - The origin of the universe
  - The fundamental laws of nature (Grand Unified Theories)
  - The origin of life
  - …

- With the start of operation of the *Large Hadron Collider* at CERN in Geneva, physics has entered a new era

  Ground-breaking discoveries are expected, which might change our understanding of Nature