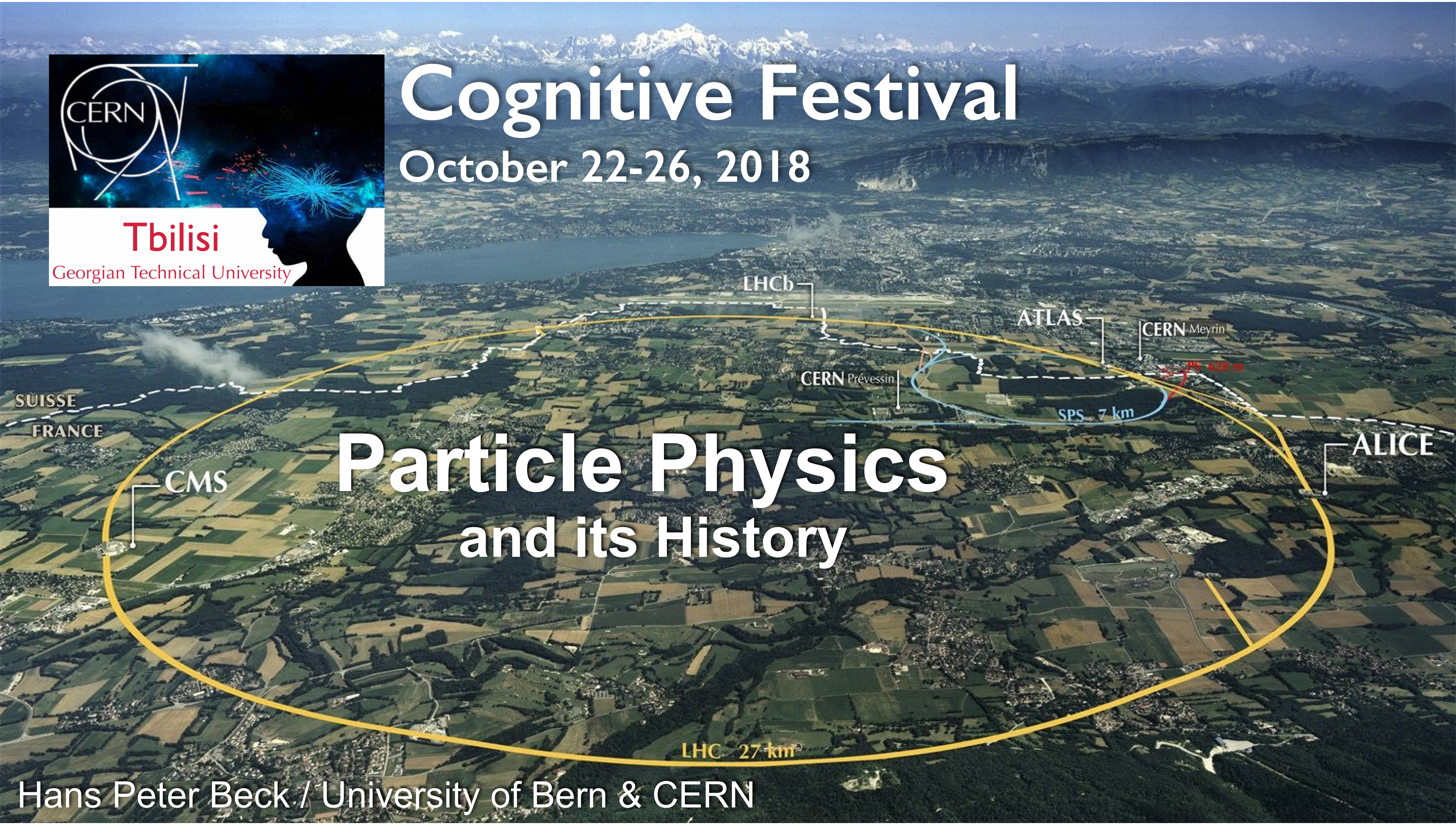
Cognitive Festival

October 22-26, 2018

Tbilisi
Georgian Technical University

Particle Physics
and its History

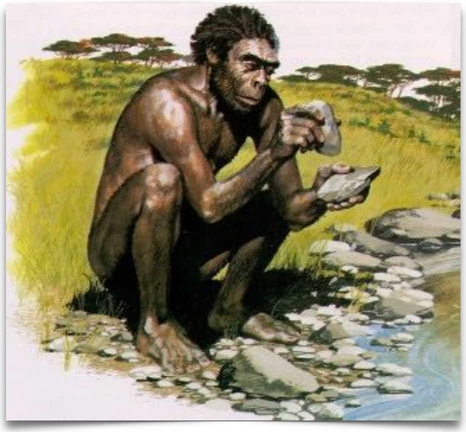


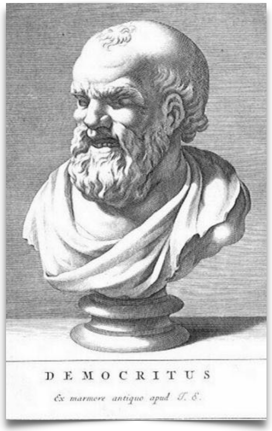
Hans Peter Beck / University of Bern & CERN

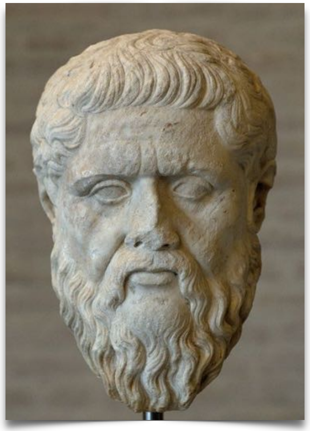
Ancient building blocks of the Universe

What is the world made out of ?

What are we made out of ?



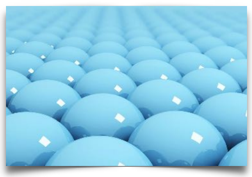




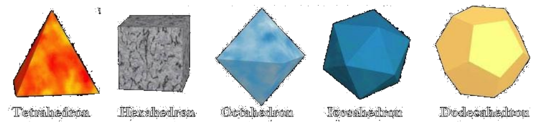
Ogg (many years BC)
What is inside?

Aristotele (384–322 BC)
Space and all matter
is continuously filled

Democritus (460–371 BC)
Matter consists of indivisible
elementary particles
atomos (ατομος) = indivisible



Plato (ca 428–348 BC)
Elementary symmetries

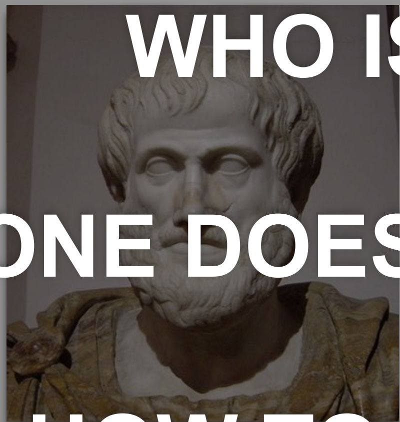
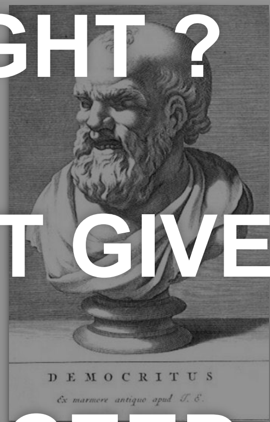


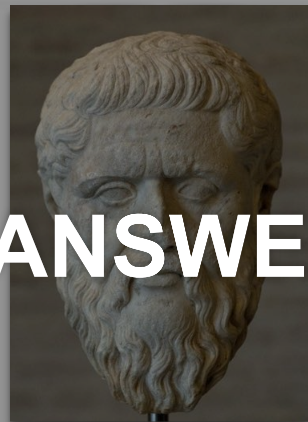
Fire Earth Air Water Ether

What is the world made out of ?

What are we made out of ?

WHO IS RIGHT ?



THINKING ALONE DOES NOT GIVE THE ANSWER !

HOW TO PROCEED ?

Ogg (many years BC)
What is inside?

Aristotele (384–322 BC)
Space and all matter is continuously filled

Democritus (460–371 BC)
Matter consists of indivisible elementary particles
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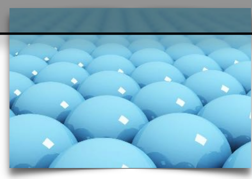
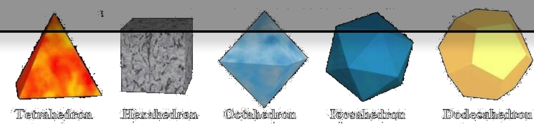
Plato (ca 428–348 BC)
Elementary symmetries

DO EXPERIMENTS AND GET THE ANSWERS !



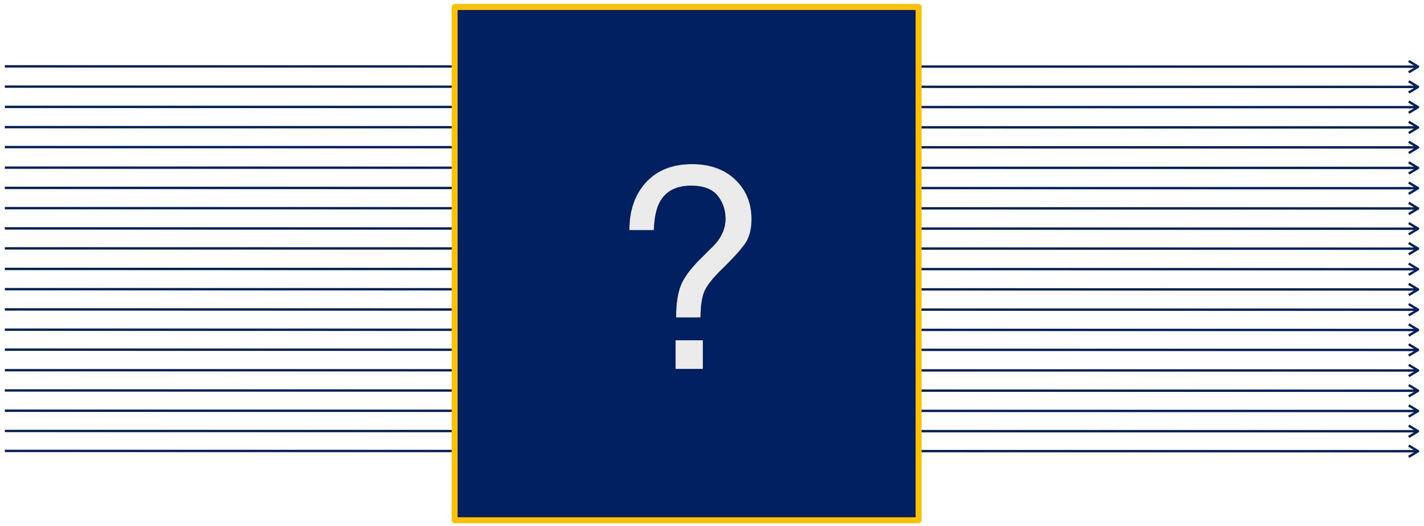



Fire Earth Air Water Ether

Scattering experiments

The path to an understanding
of the fabric of space and time

Scattering Particles – what is in the Black Box ?



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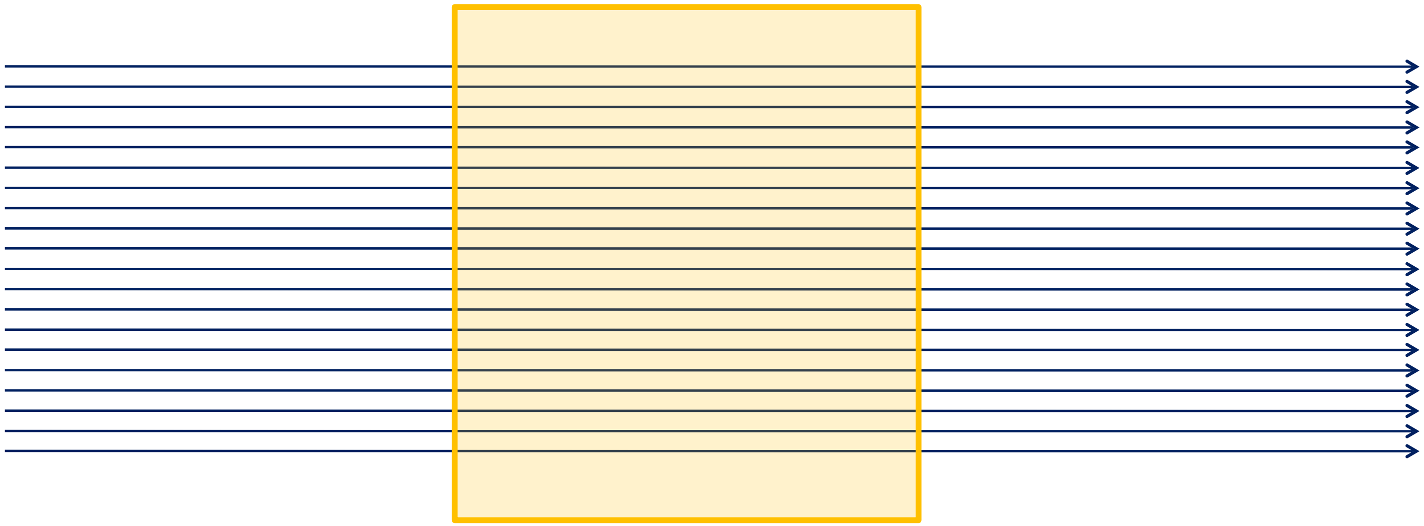

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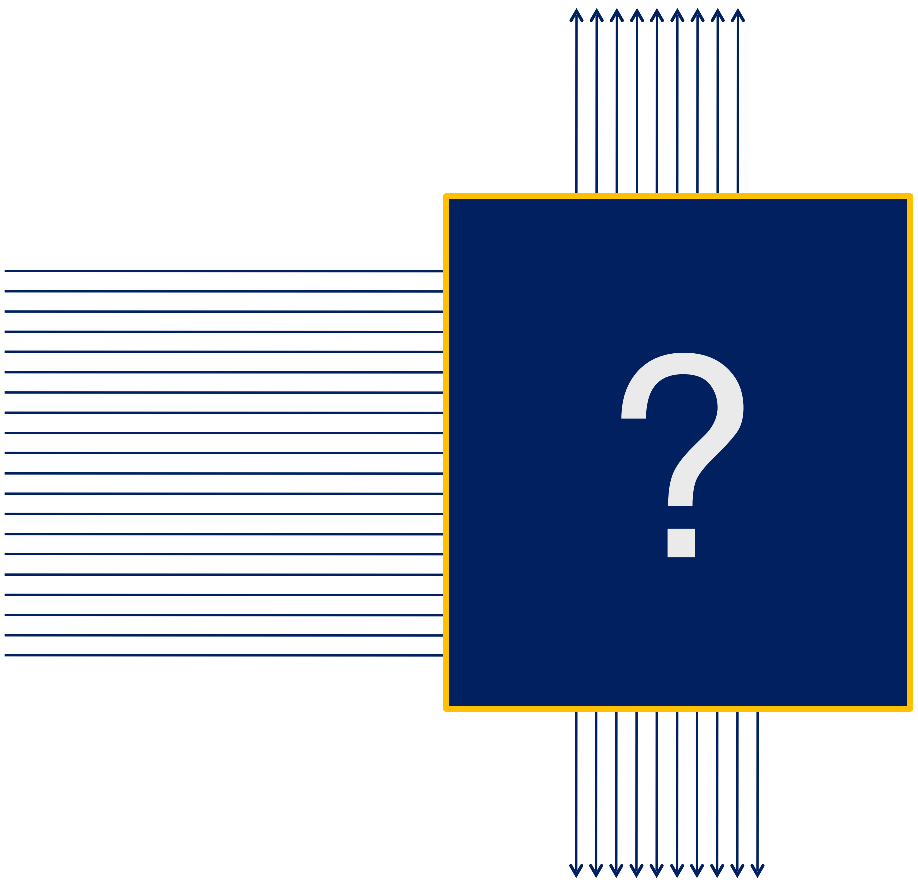

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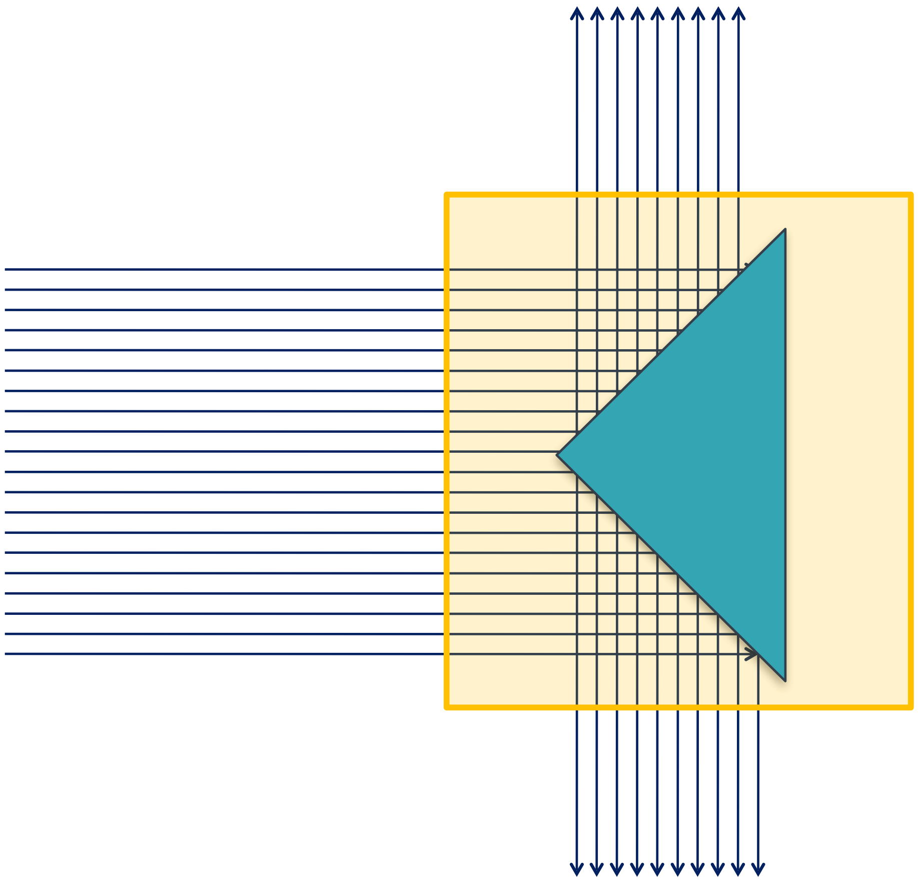

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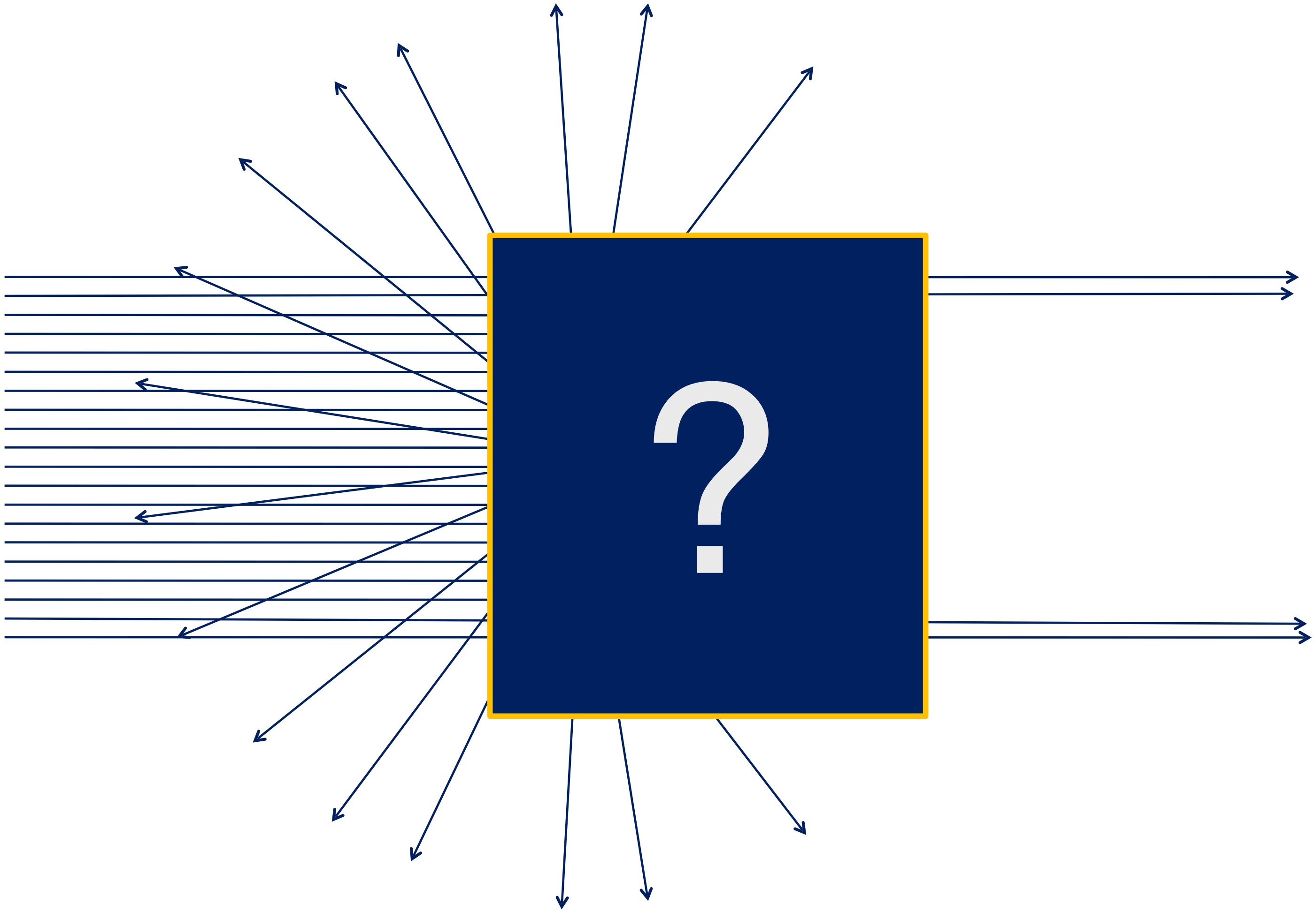
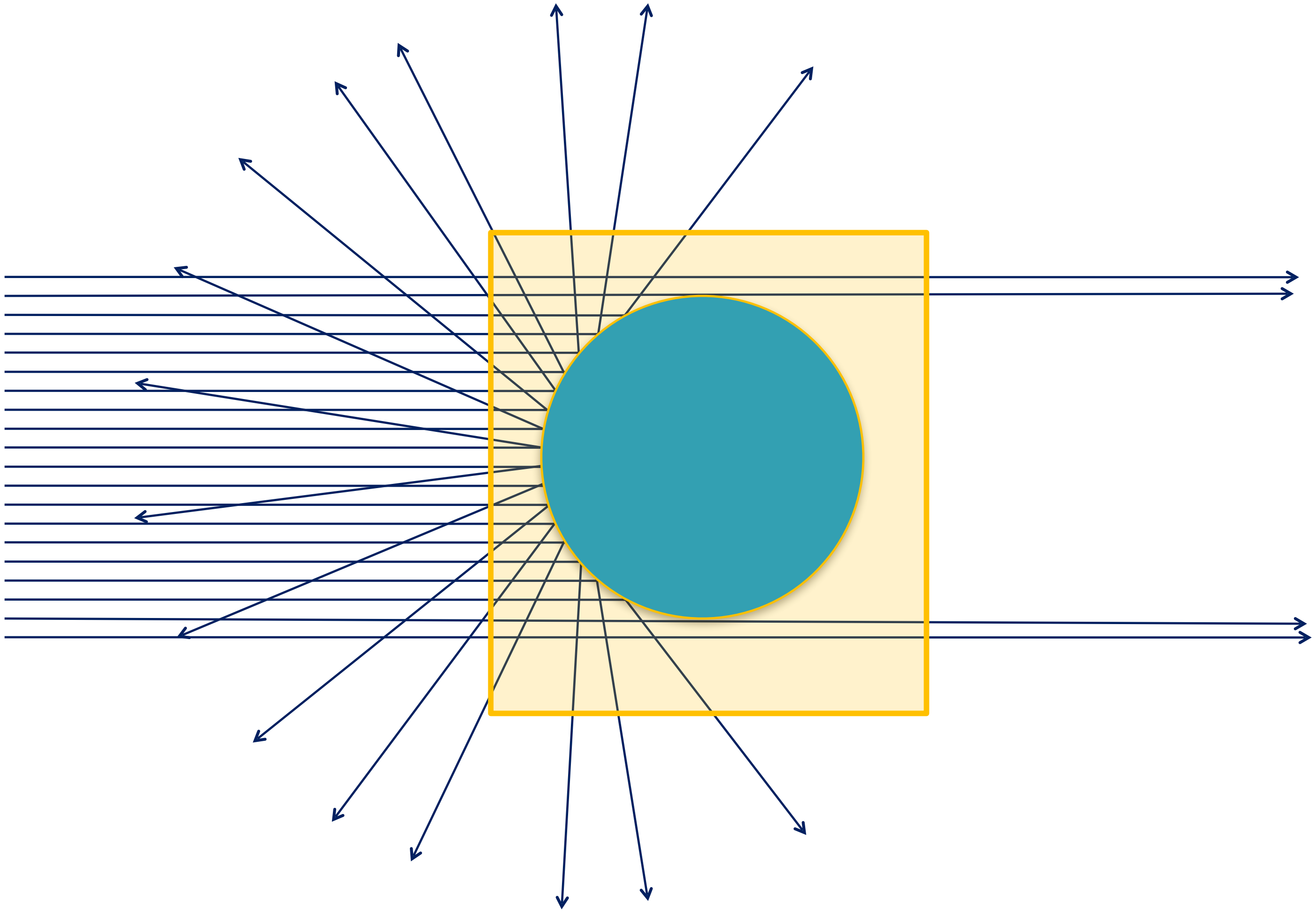


Scattering Particles – what is in the Black Box ?



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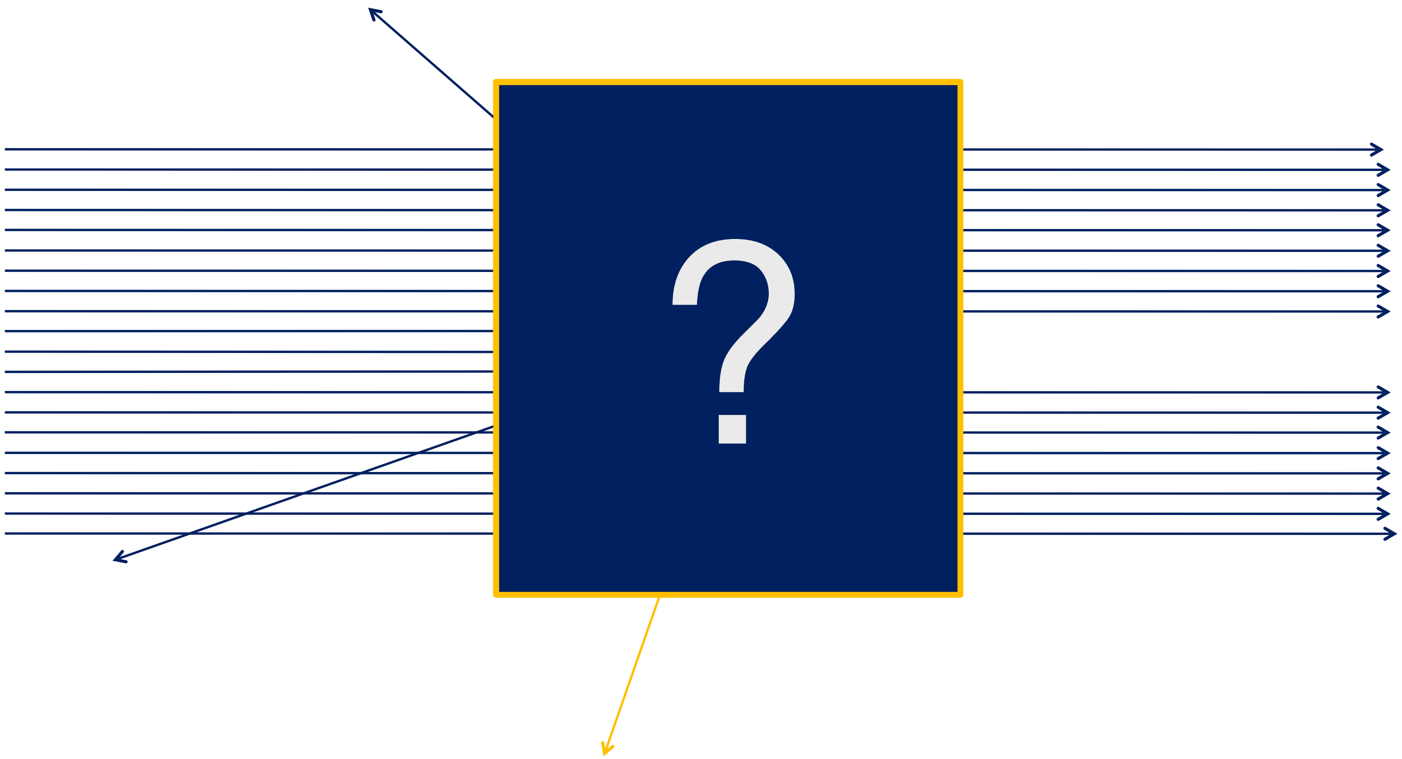

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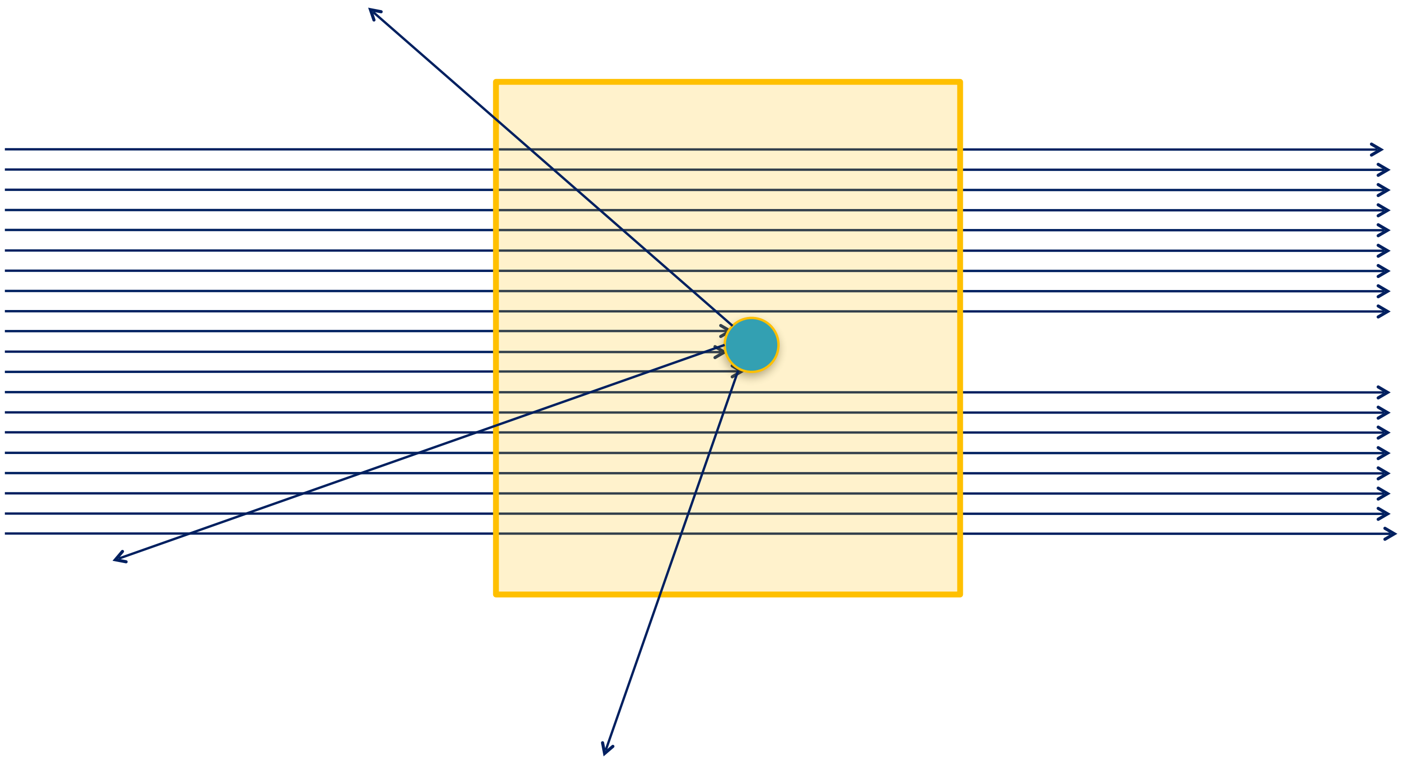


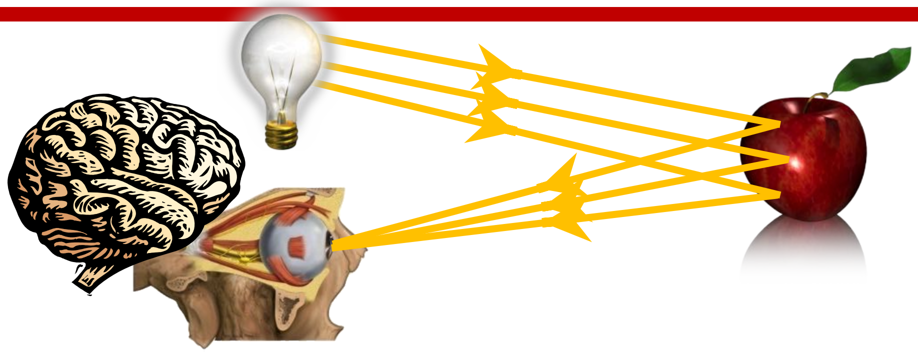
Scattering Particles – an every day experience

Too 'see' an apple, you need to scatter particles off it.

- Photons are the particles that make up light
- The eye measures scattered photons off an apple from a light source
  - Your eyes are particle detectors, transforming the properties of photons into electric signals transported via the visual nerve to a vast processing and reconstruction engine – your brain.
    - Momentum & Energy - i.e. direction of flight and colour
    - Intensity - i.e. number of such photons per second
- The brain reconstructs out of this in a masterful online-reconstruction of the data in real time the

→ Shape, Size, Distance, Colour, Texture of the Apple

Resolving small scale objects



The wavelength of the photons determines the resolution power to see small scale structures.

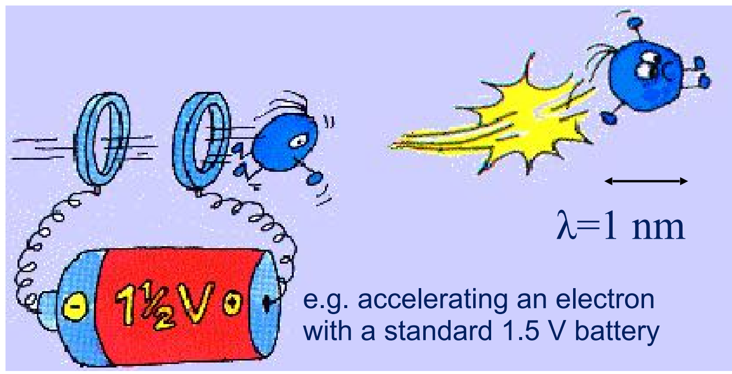
Even the strongest microscope operating with light
is incapable of resolving structures of the size of an atom.

All particles have an associated wavelength → quantum mechanics

Particle wavelength: $\lambda = \frac{h}{p} = \frac{\text{Planck's constant}}{\text{momentum}}$

One needs huge momenta to resolve small scale structures

→ One needs big accelerators to go deep into the heart of matter



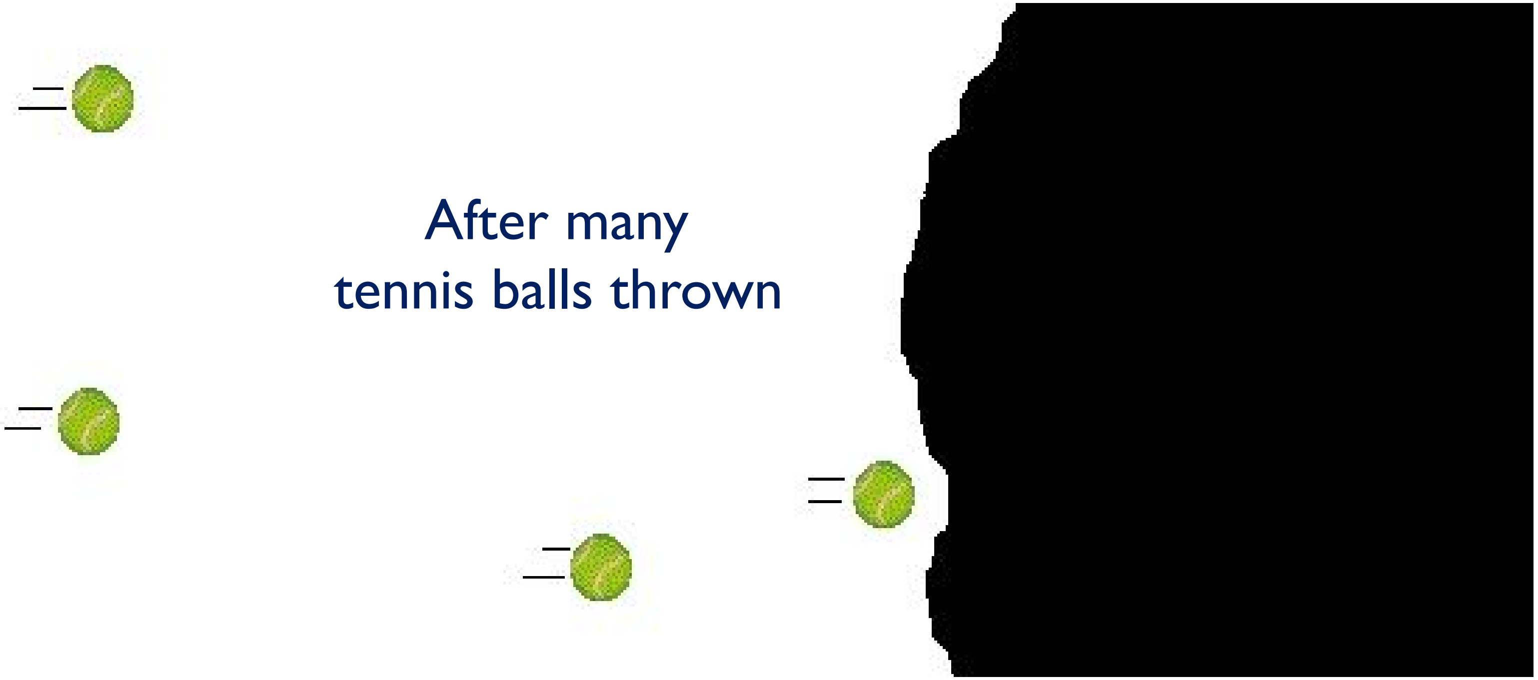
Unknown object in a cave

Wavelength ~ diameter of a basket ball

After many
basket balls thrown

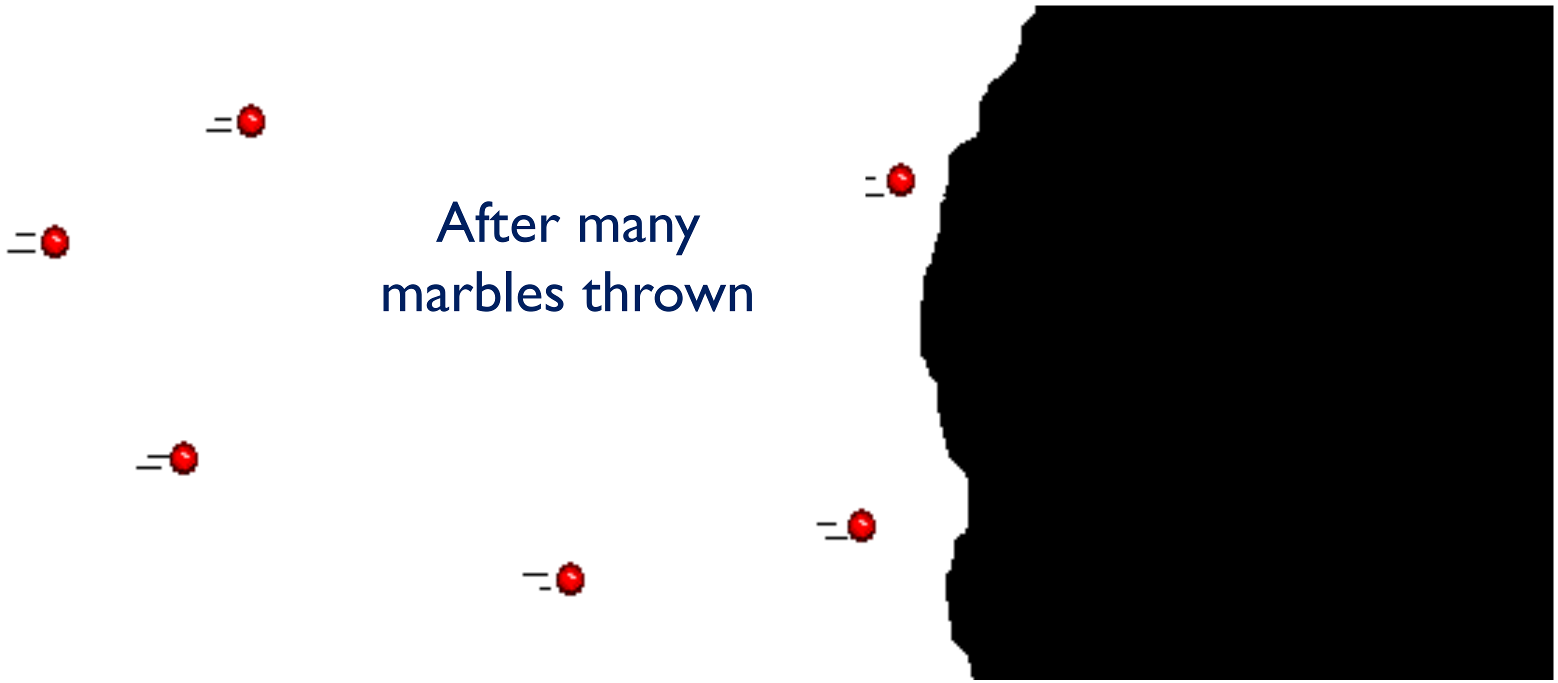
Unknown object in a cave

Wavelength ~ diameter of a tennis ball



Unknown object in a cave

Wavelength ~ diameter of a marble

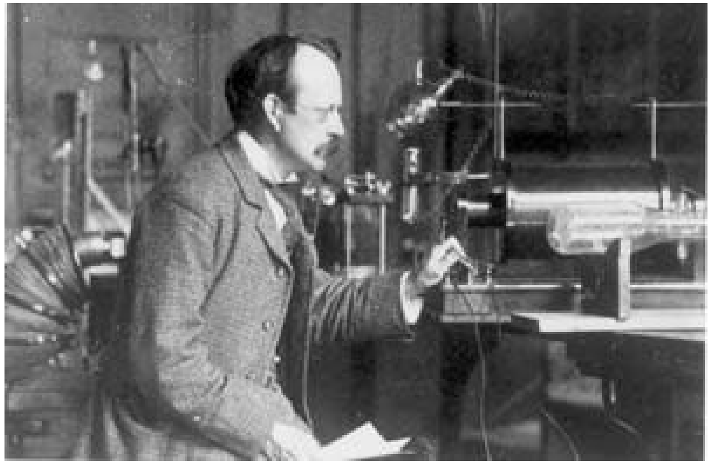


better dash off !!

A brief historic overview

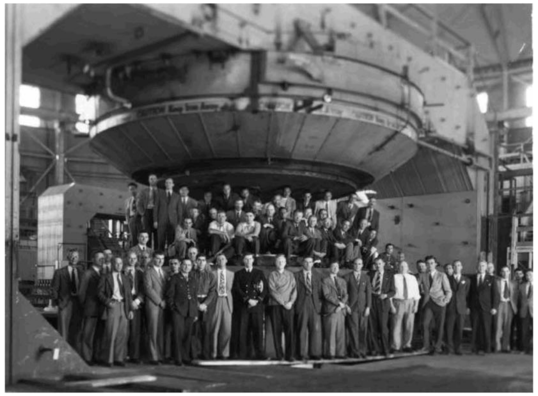
using particle accelerators at ever increasing energies

120 years of accelerating particles

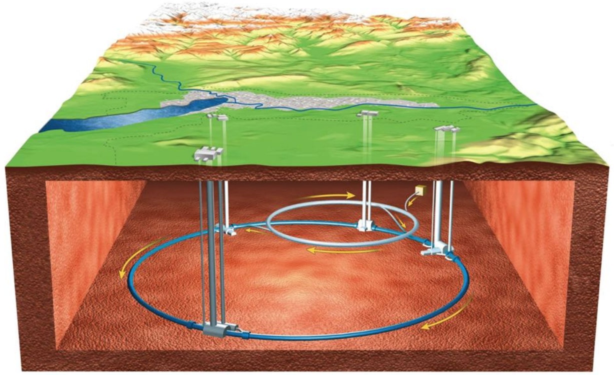


1897 Accelerating electrons
Cathode ray tube
J.J. Thomson

1931 First circular accelerator
Ernest O. Lawrence & M. Stanley Livingston



1940



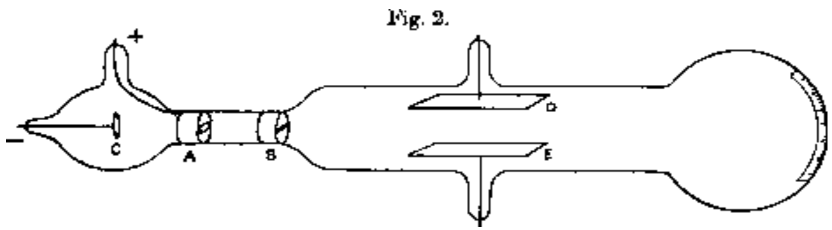
Today: LHC

1894-1897 discovery of the electron

J.J. Thomson discovered the electron and also determined its mass through **scattering of cathode rays at gas molecules** in the rest gas of the cathode ray tube.

"Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?" (J.J. Thomson)

Cathode Rays Philosophical Magazine, 44, 293 (1897)



Cathode ray tube:

Thomson's electron accelerator

$$m_e \approx \frac{m_H}{1836}$$

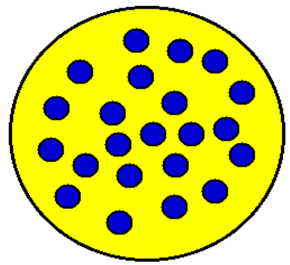
Atoms are not elementary particles

Sir Joseph John Thomson
*18 December 1856, Manchester
†30 August 1940, Cambridge

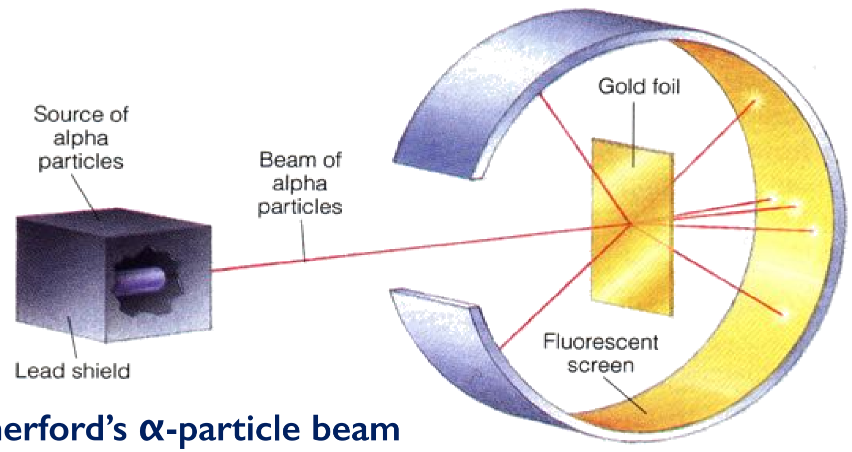
Nobel Prize 1906
„in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases."

Thomson's model of the inner structure of the atom

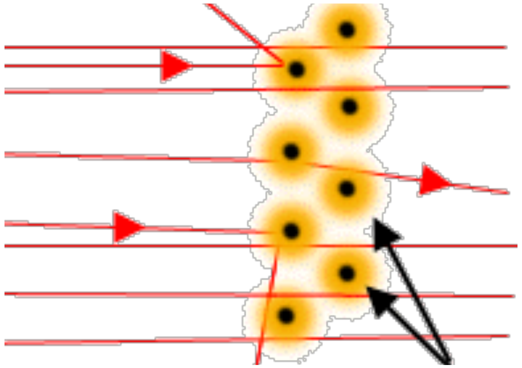
- ◇ atoms consist out of a positively charged sphere
- ◇ negatively charged electrons are evenly distributed
- ◇ the radius r of an atom is $r \sim 10^{-10}$ m.



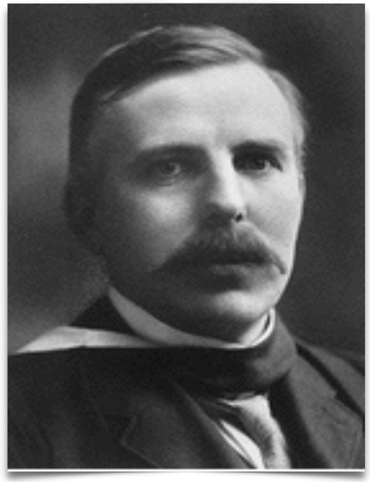
1906-1911 Structure of the atom



Rutherford's α-particle beam



Gold atoms in a gold foil



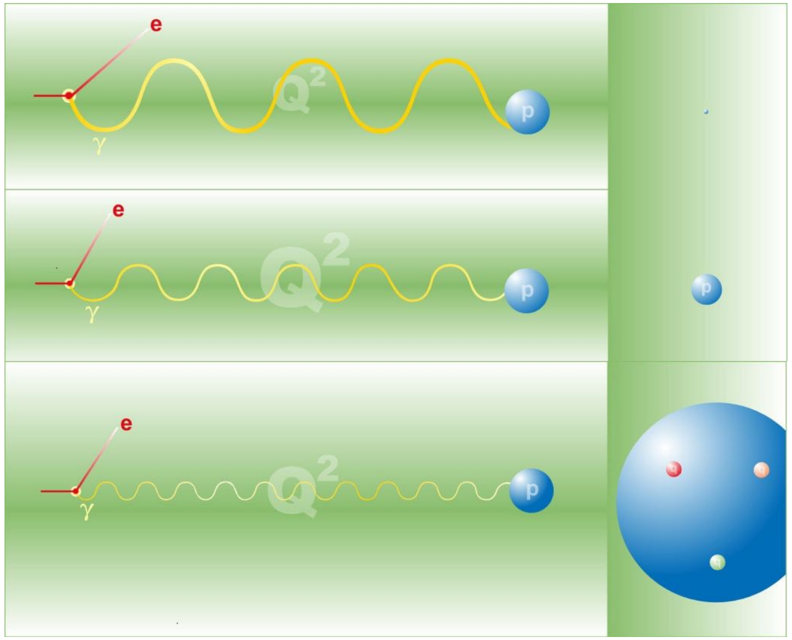
Atoms have a positively charged, massive nuclei.
Negatively charged electrons surround the nuclei
radius of the nuclei ≈ 10^{-15} m ≈ 10^{-5} x atomic radius
mass of the nuclei ≈ mass of the atom

Lord Ernest Rutherford of Nelson
* 30 August 1871, Brightwater, New Zealand
† 19 October 1937, Cambridge, UK

Nobel Prize 1908 in Chemistry
„for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

The scattering of alpha and beta particles by matter and the structure of the atom
By E. Rutherford, Phil.Mag.Ser. **6** 21**,** p. 669-688, (April, **1911**)

The inside of protons….



The **wavelength** of the **photon** corresponds to the **diameter of the projectile used**

- basket ball
- tennis ball
- marble

The higher the collision energy, the smaller the wavelength of the penetrating photon and thus higher resolving power.

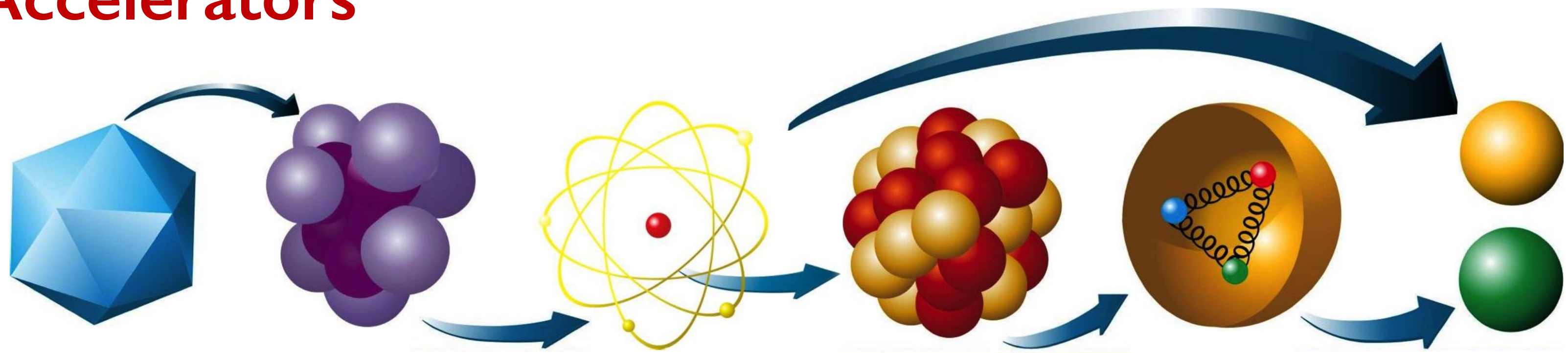
➢ **Protons** and **neutrons** consist out of **quarks** and **gluons**.

➢ Three quarks (valence-quarks) determine the quantum numbers of the proton (or neutron).

➢ Valence-quarks are immersed in a sea of virtual quark–anti-quark pairs and gluons.

The Innermost of Matter Revealed

using Accelerators



1/10´000´000 1/10 1/10´000 1/10 1/10´000

≷ 0,01 m Crystal

10^{-9} m Molecule

10^{-10} m Atom

10^{-14} m Nuclei

10^{-15} m Proton

$<10^{-19}$ m Quark, Electron

Pinhead:

10^{-3} m = 0,001 m

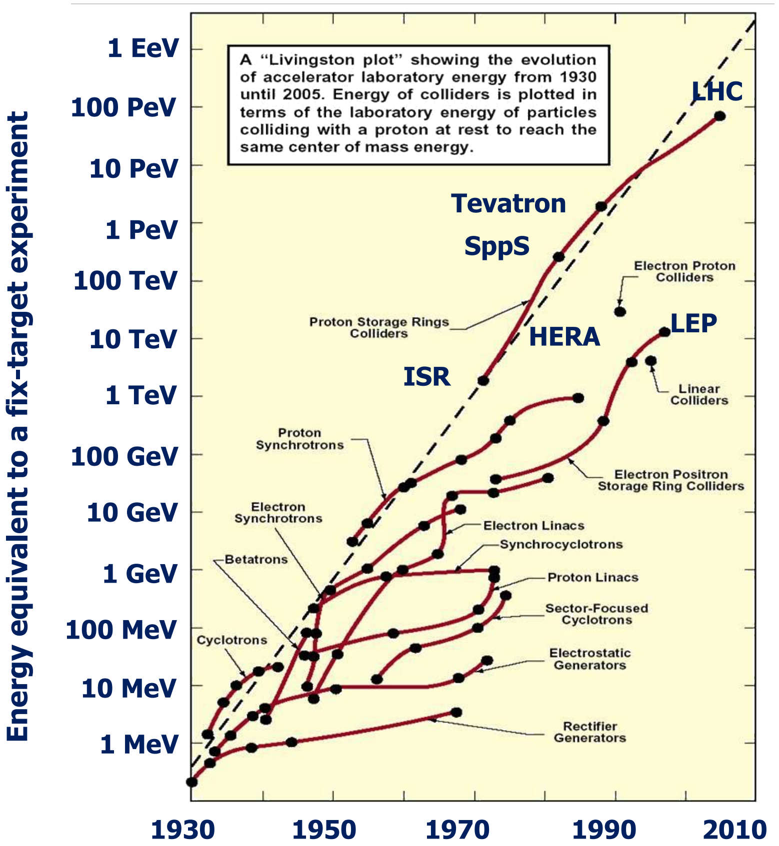
Electron, Quark:

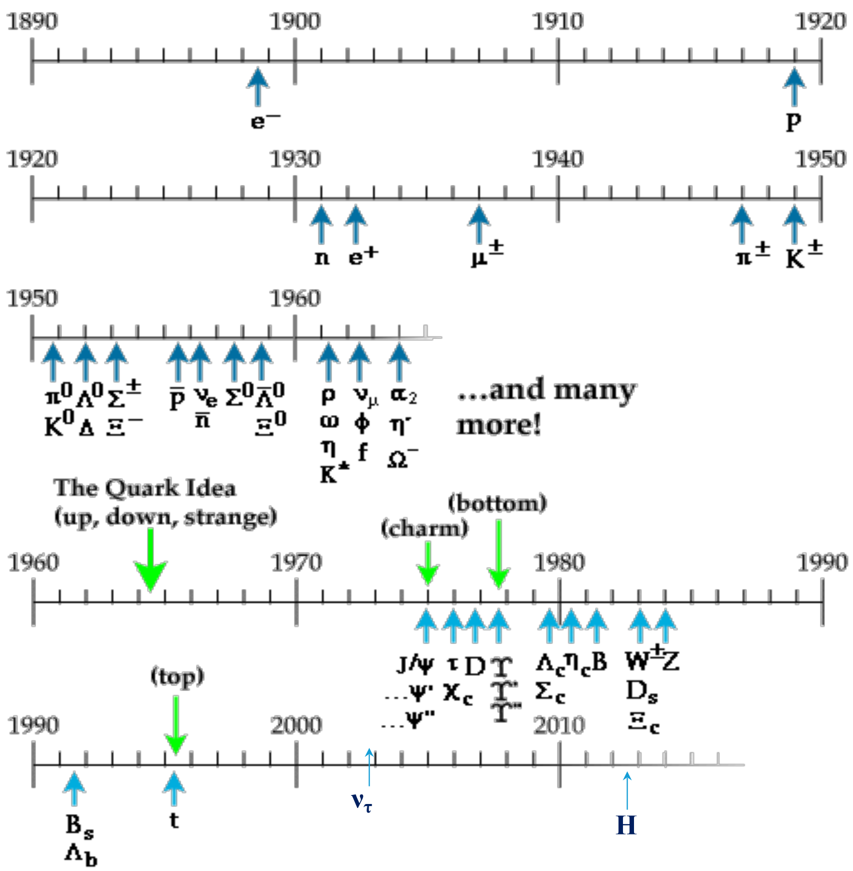
$< 10^{-19}$ m = 0,000´000´000´000´000´000´1 m

(no further inner structure ??? Who knows?)

If an atom’s radius would be as large as from Tbilisi to CERN (3000 km), the LHC could still resolve 3 millimetre scale objects.

Accelerators and discovered particles





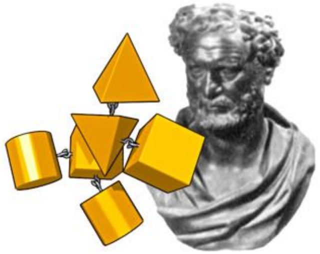
$$E_{Lab}^{FT} = E_{cm}^2 \big/ 2m_p$$

E_{Lab}^{FT} Fix-target experiment, beam energy measured in laboratory system

E_{cm} Collision energy measured in centre of momentum system

Matter and Forces

Matter, Space and Forces



Matter is composed out of building blocks → the elementary particles.

The variety of all complex systems and everything in nature and the whole Universe is composed out of these elementary particles.

These elementary particles have no inner structure, they show no spatial dimension. → Space is probably completely empty

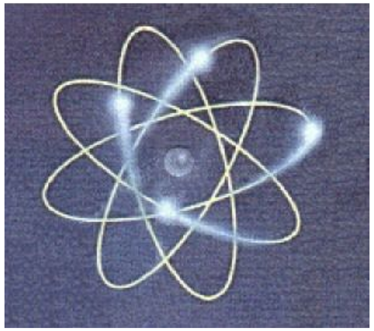
But why does matter – e.g. a table – appear massive?

The particles interact with each other → fundamental forces!

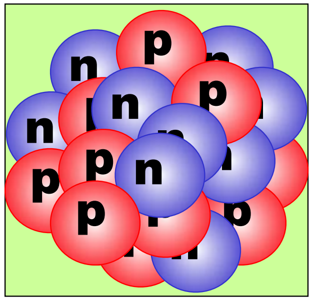
What are these forces, that bind nature together?

Natures four fundamental Forces

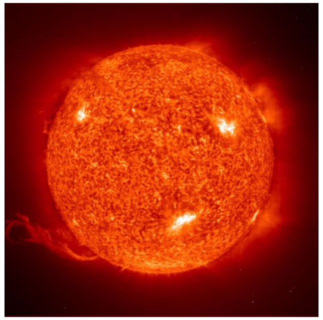
Gravity



electro-magnetic force

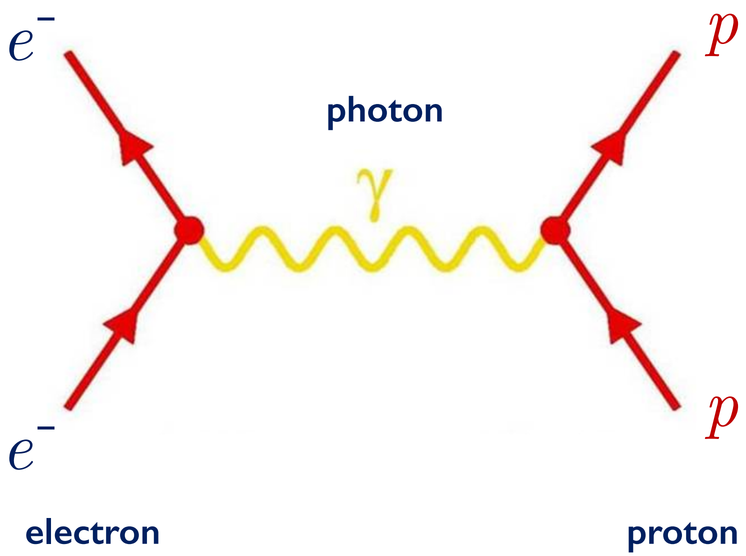


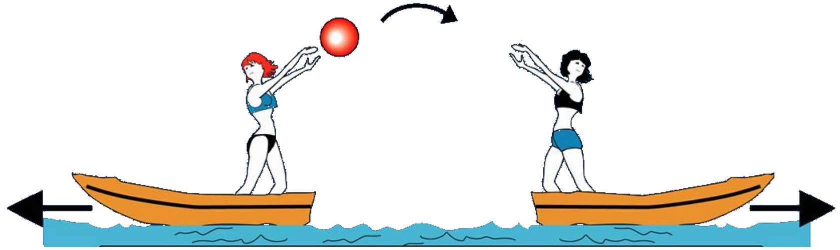
strong force



weak force

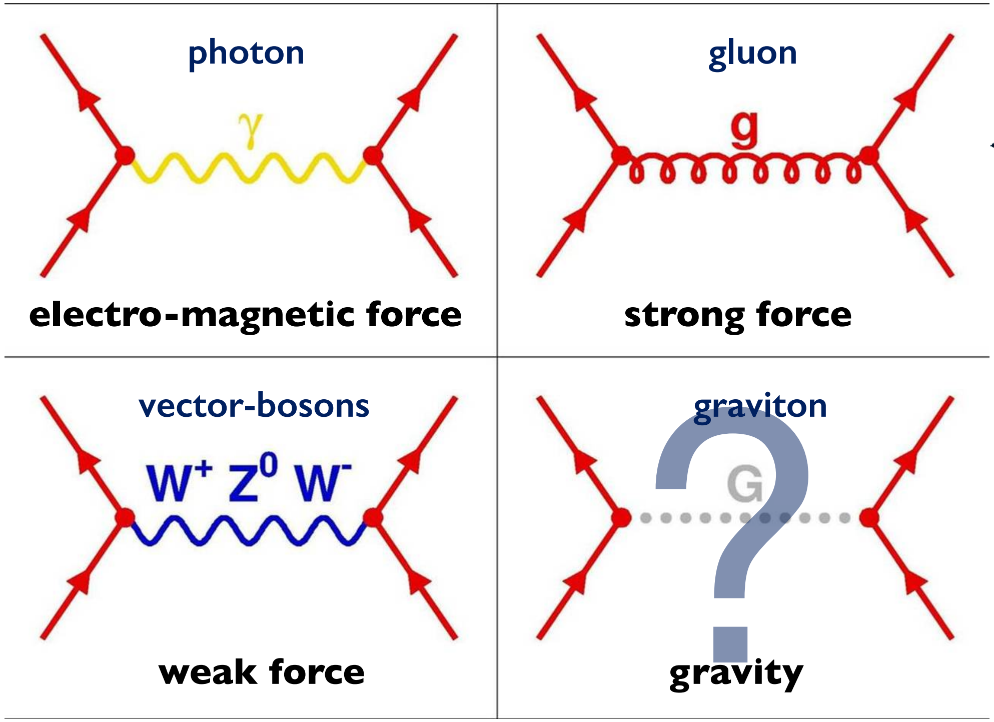
Forces

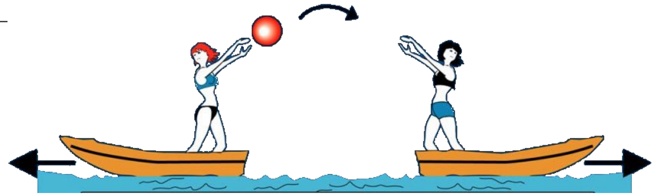




Forces between particles are mediated by particles!

Force mediating Particles





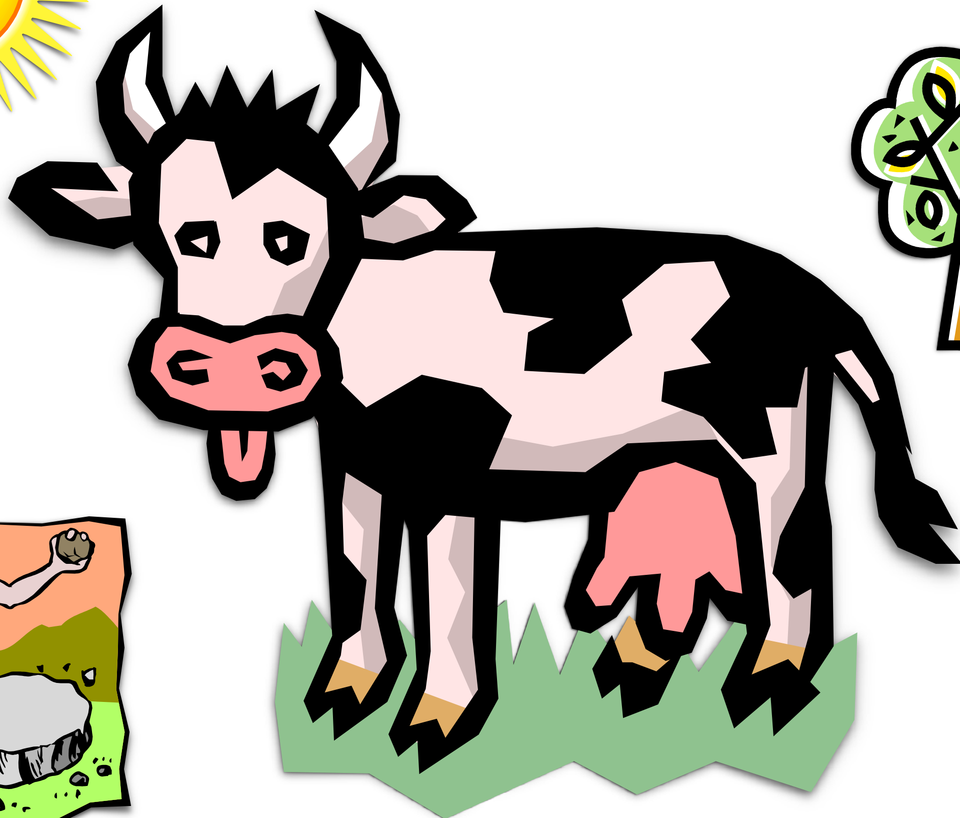
Photons, gluons and vector-bosons are well known and well established

The graviton lacks experimental evidence...

A Universe full of Particles

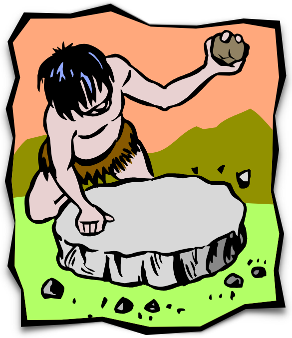
Every cow, all the trees, the stones, humans, the planets, the sun, the stars and everything else consist of

- **At least 99.999…999% empty space**
- **Small particles ($<10^{-19}$ m – point like?)**
  - **electrons**
  - **up-quarks**
  - **down-quarks**



they are hold together by

- **photons**
- **gluons**
- **vector-bosons**
- **gravity**



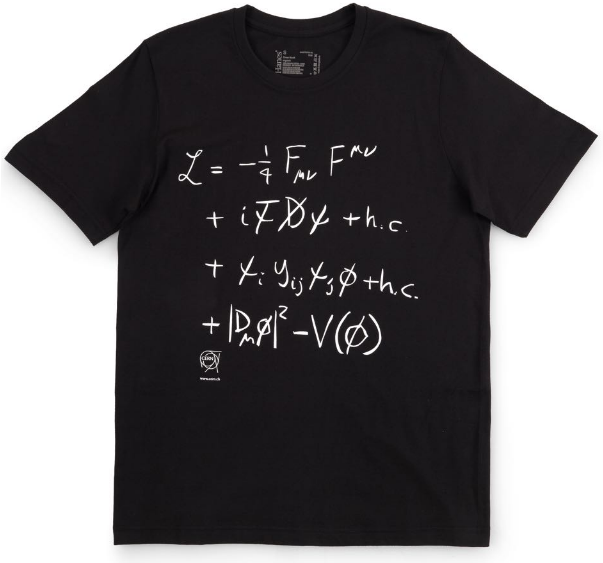
Furthermore, vector-bosons (weak force) transmute **electrons** into **neutrinos**

- **Every human radiates of 340 million neutrinos – daily!** (20 mg ^{40}Ka)

The Standard Model

of Particle Physics

The Standard Model fits on a T-shirt



An exact description of all experimental results ever made (except gravity…)

Basic symmetries, **quantum mechanics** and **special relativity** are enough to understand the dynamics of elementary particles – that are the building blocks of the Universe.

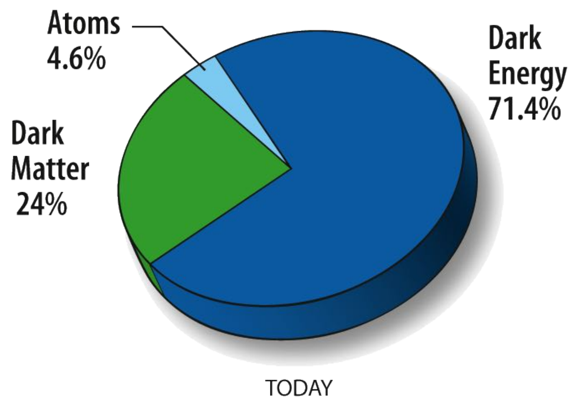
I would say, quite an achievement…

1st line: the boson fields of the basic forces (electromagnetic, weak, strong)

2nd line: interactions involving quarks and leptons.

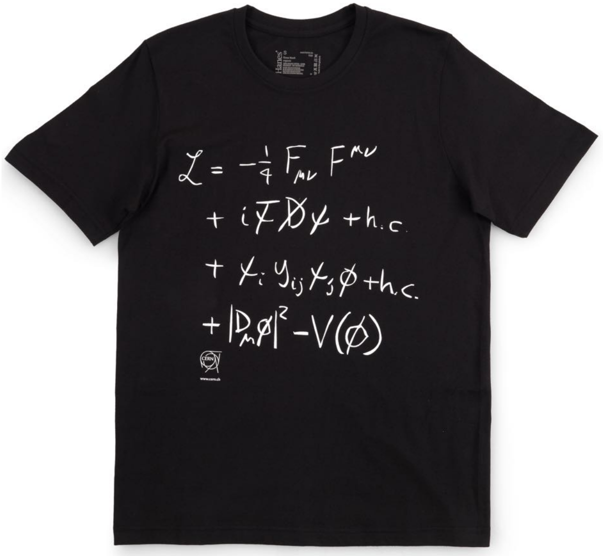
3rd line: mass generation of quarks and leptons through their interaction with the Higgs-field ϕ.

4th line: mass generation of bosons and the Higgs vacuum.



well, some questions remain…
the work hasn't finished !

The Standard Model fits on a T-shirt



is a short notation of...

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + \\
m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \\
\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + \\
(\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 + \\
\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] + \\
\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \\
\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] - \\
\tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \\
\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \\
\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \\
\bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

1st line: the boson fields of the basic forces (electromagnetic, weak, strong)

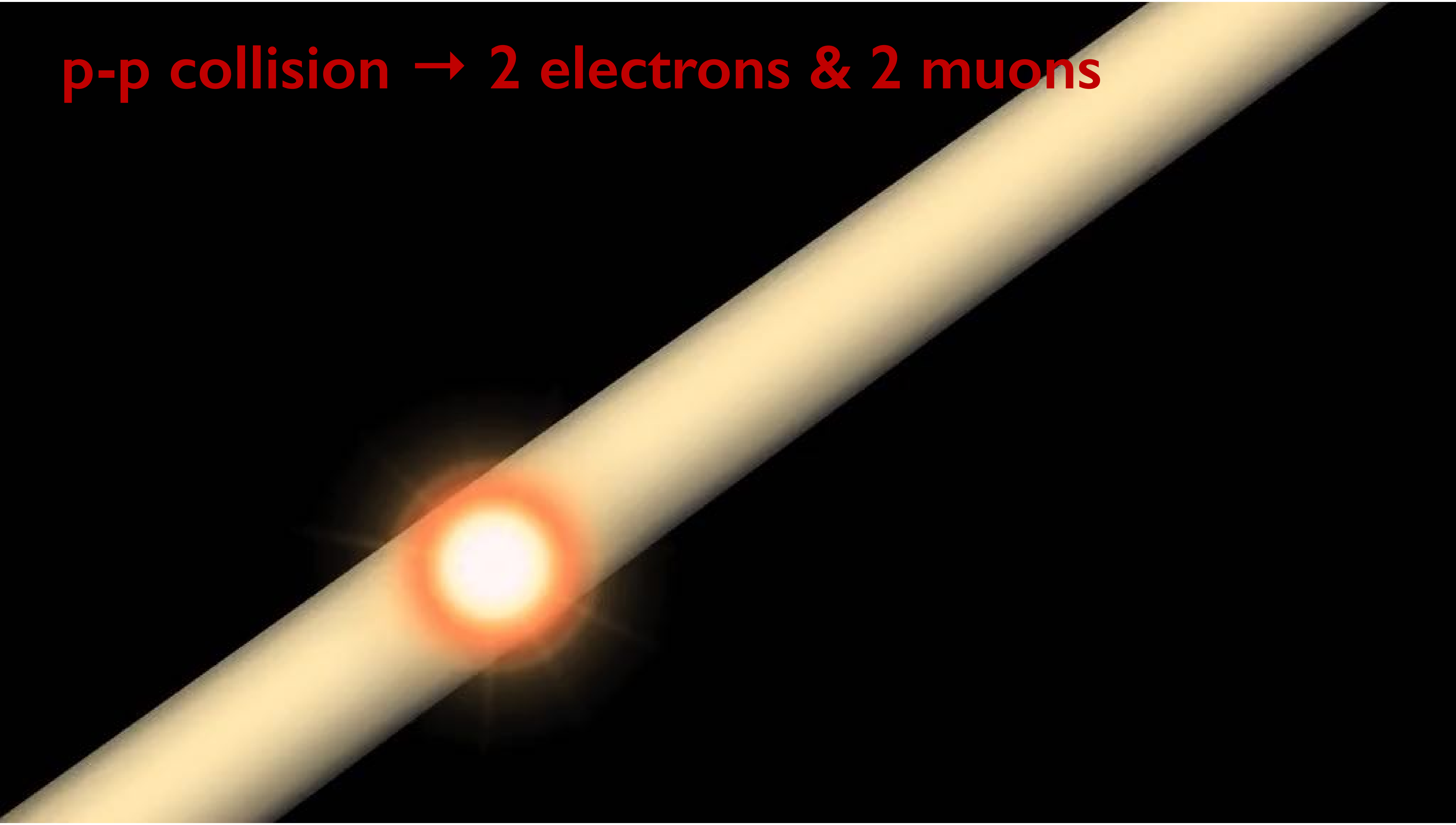
2nd line: interactions involving quarks and leptons.

3rd line: mass generation of quarks and leptons through their interaction with the Higgs-field ϕ.

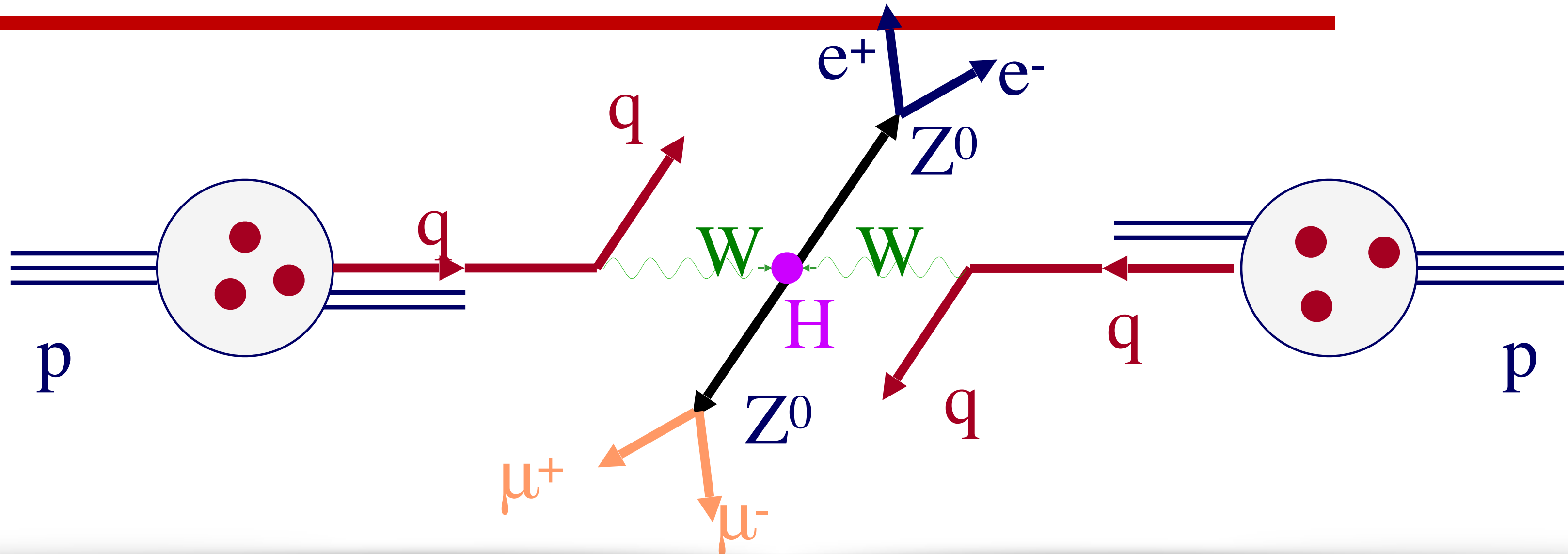
4th line: mass generation of bosons and the Higgs vacuum.

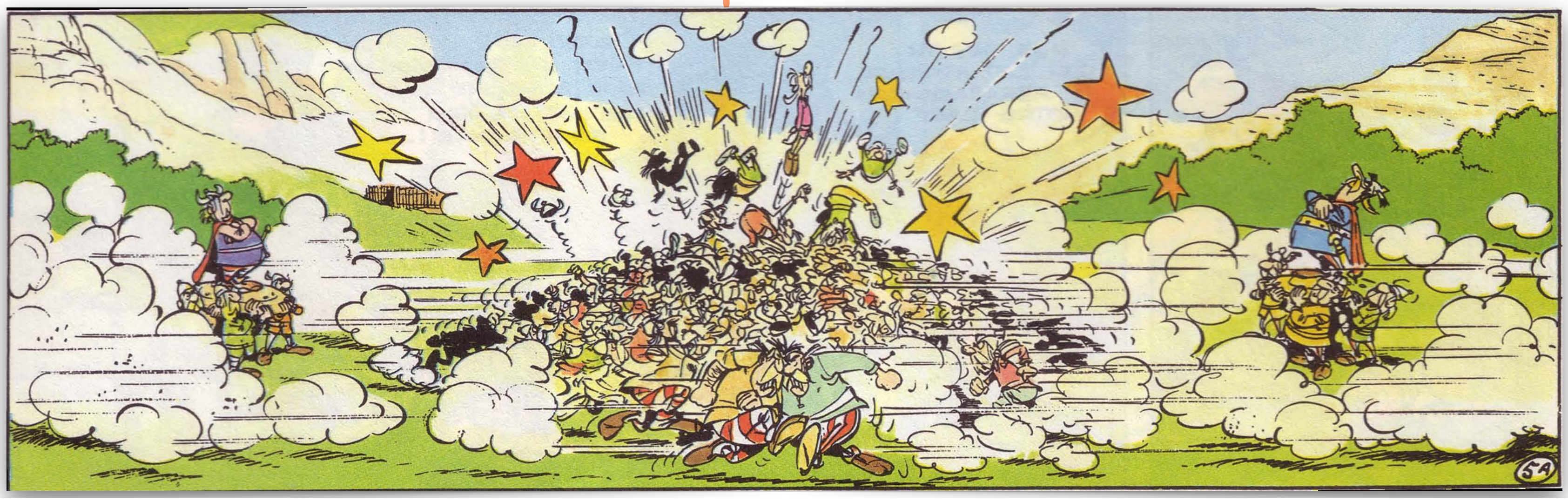
Higgs

p-p collision → 2 electrons & 2 muons



Higgs production in *p*-*p* collisions





CERN – 4th July 2012

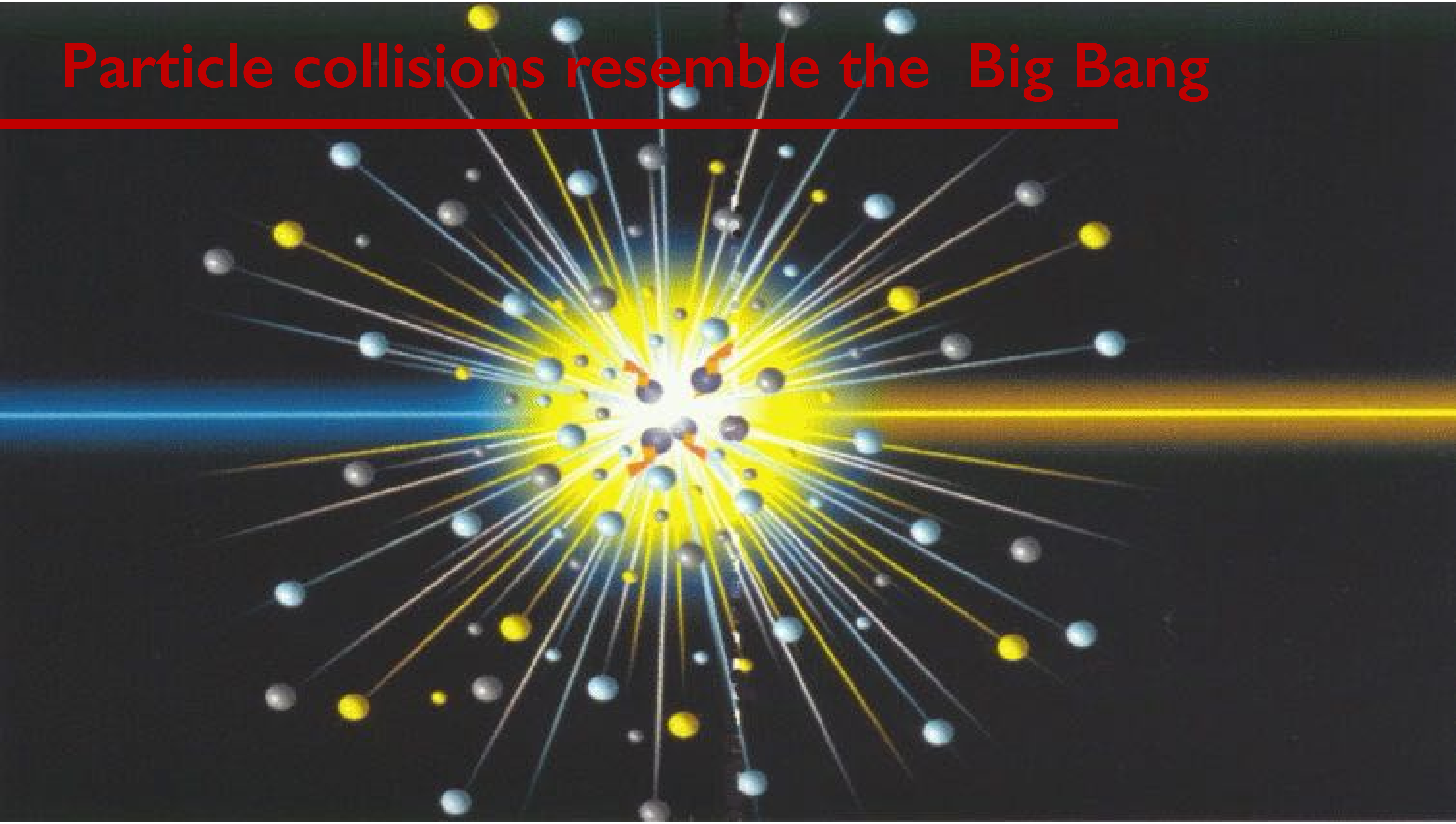
Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Particles and Cosmology

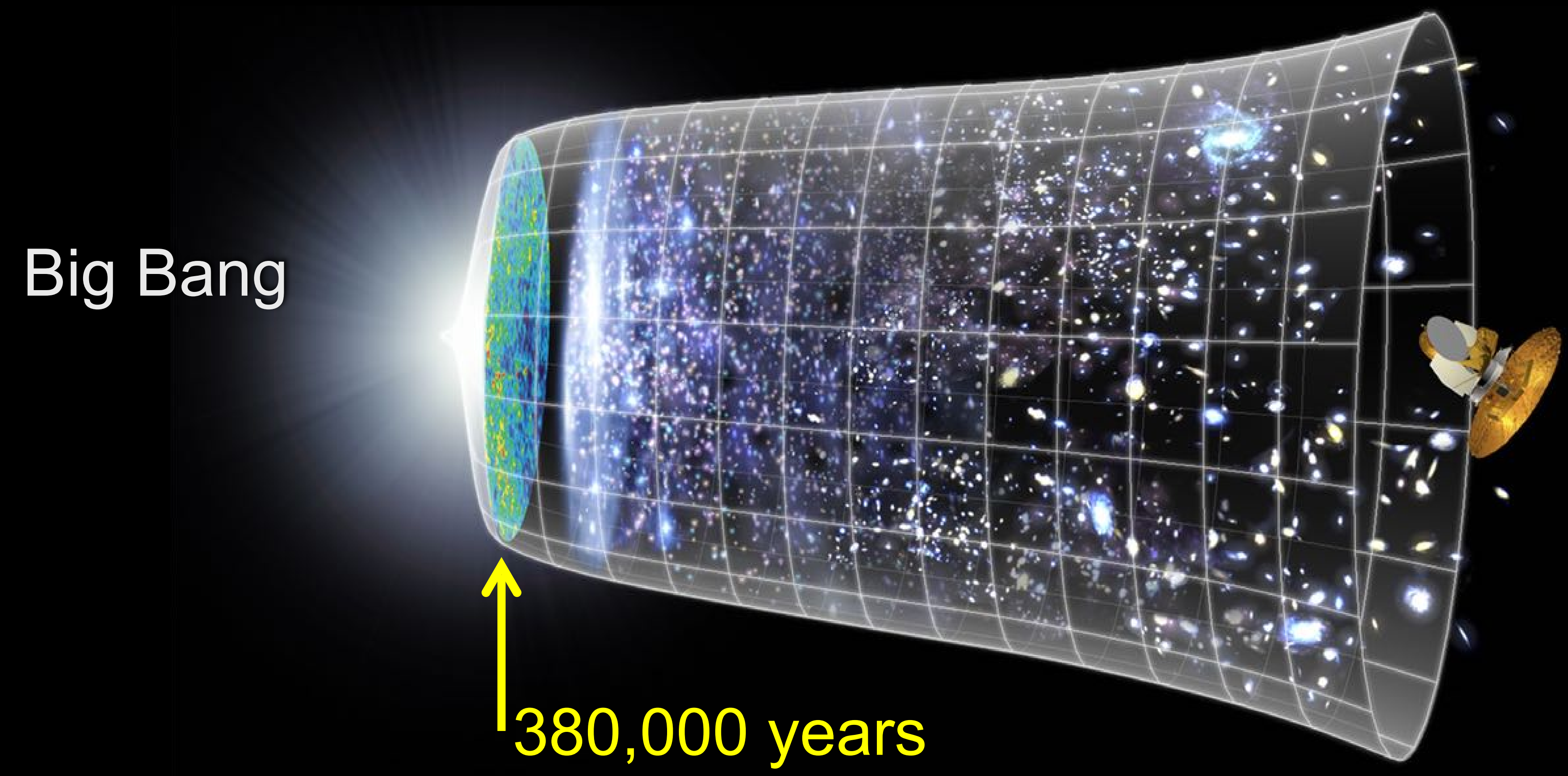
Let’s draw the Universe

Particle collisions resemble the Big Bang



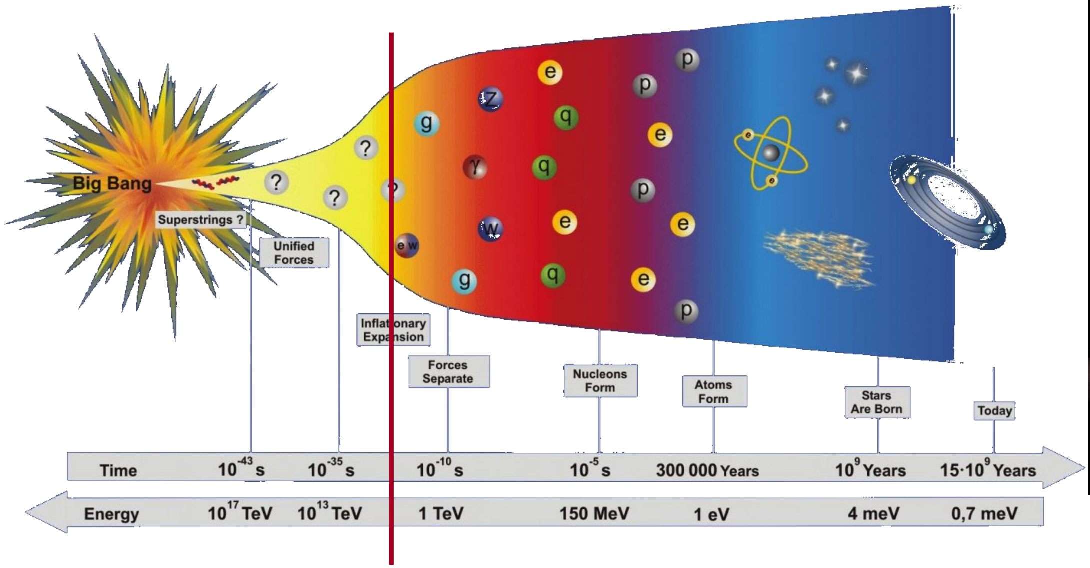
Understanding the very first moments

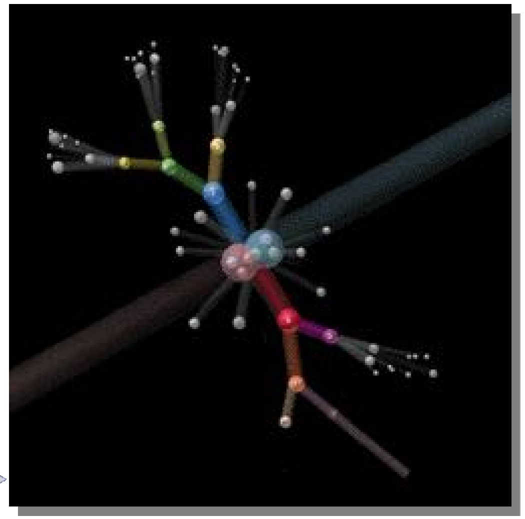
of our Universe after the Big Bang



Constructing the Universe

- Knowing the elementary particles, their properties and interactions, i.e. the Standard Model we now know how to construct the universe
  - It consists out of elementary particles
  - It all started with a Big Bang some 13.7 billion years ago
  - We can try drawing the picture of evolution of all and everything – from the Big Bang onward



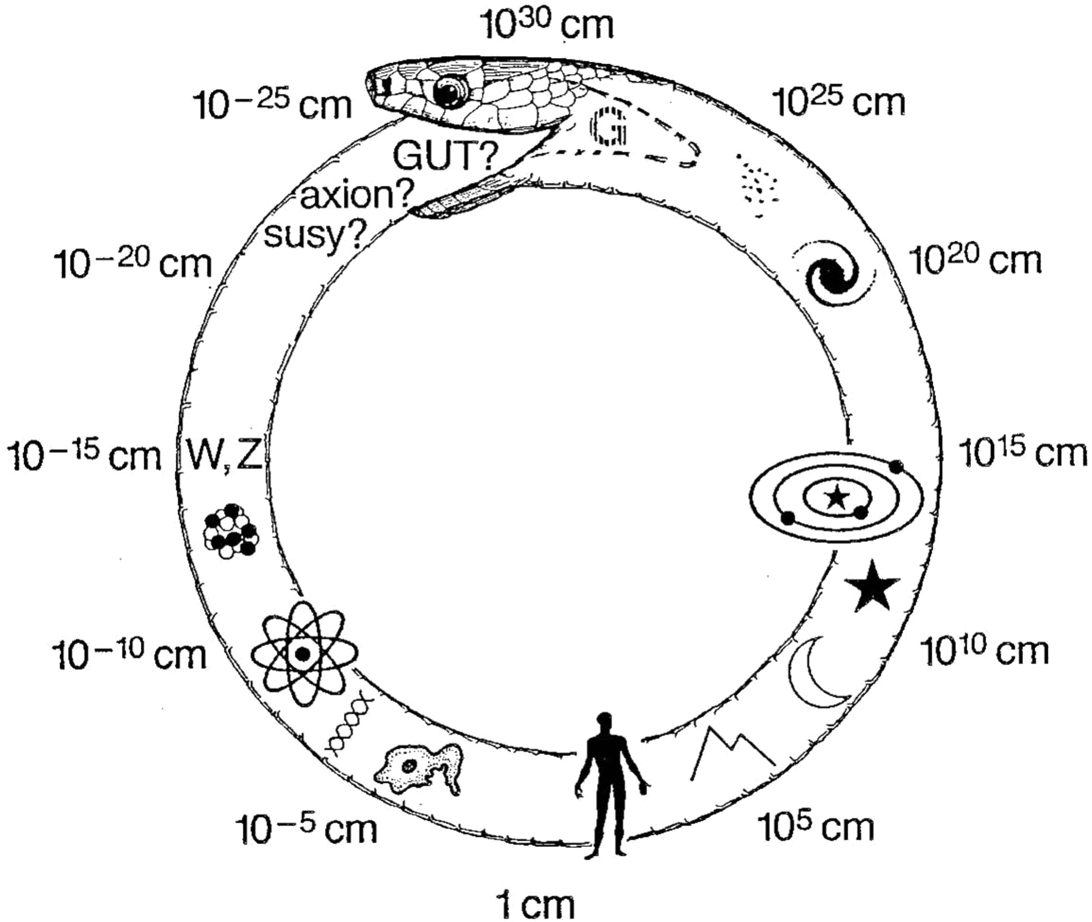


LHC 14 TeV ≙ 10^{-14} s

Particle Physics meets Cosmology

The **Ouroboros** "tail-devouring snake"

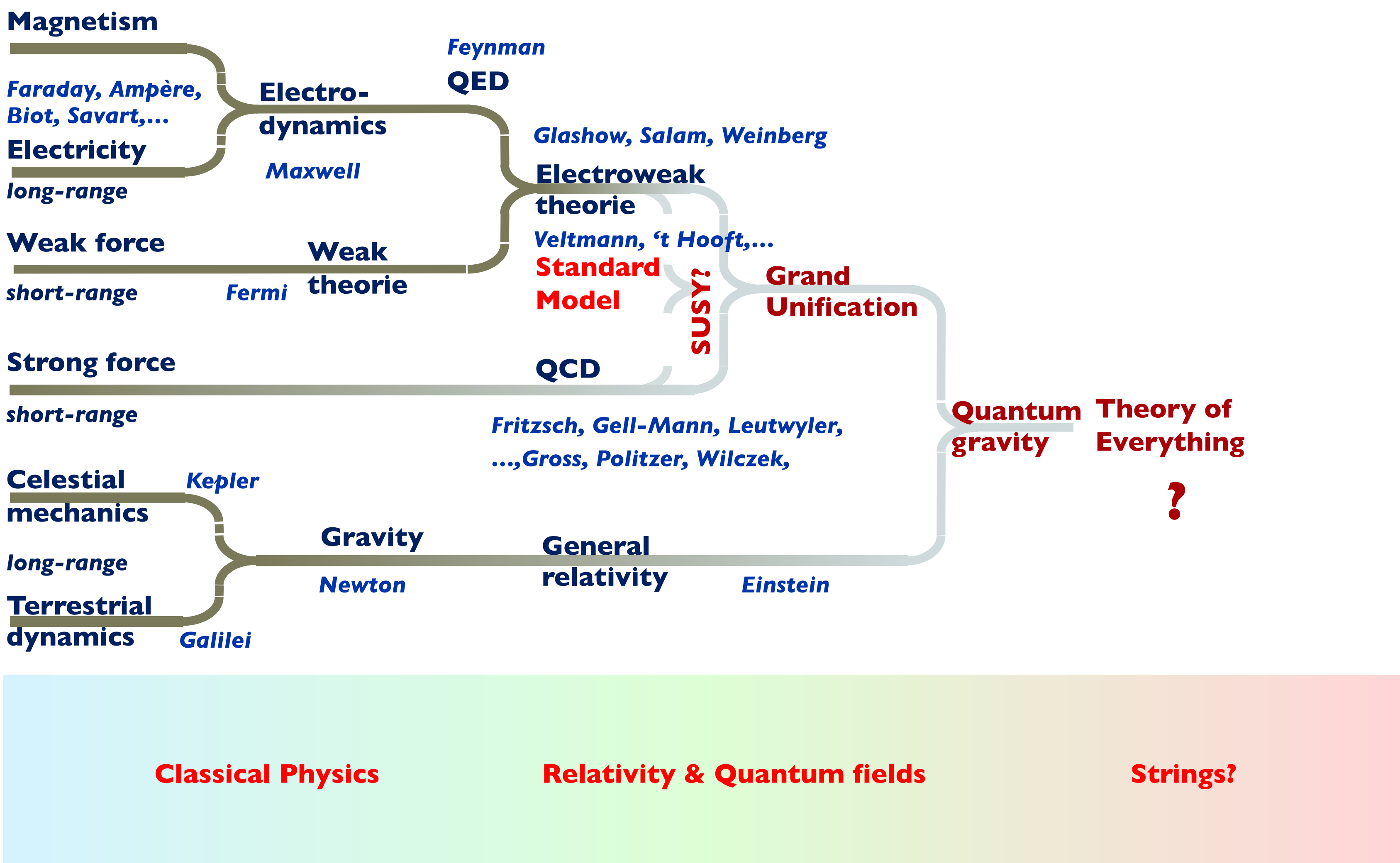
Particle Physics meets Cosmology

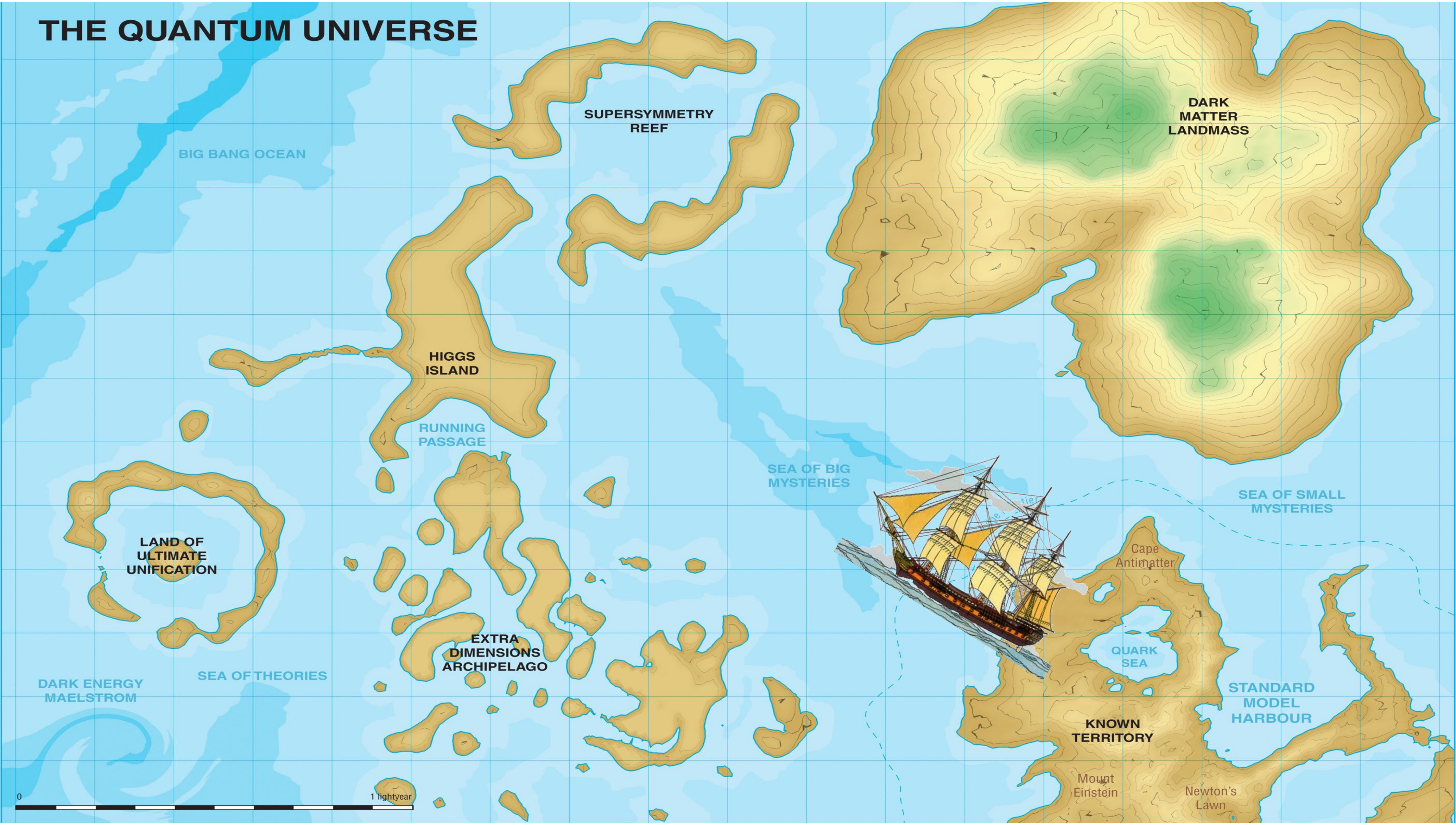


The **Ouroboros** "tail-devouring snake"

A journey to continue

Unifying Theories




THE QUANTUM UNIVERSE
BIG BANG OCEAN
SUPERSYMMETRY REEF
DARK MATTER LANDMASS
HIGGS ISLAND
RUNNING PASSAGE
SEA OF BIG MYSTERIES
SEA OF SMALL MYSTERIES
LAND OF ULTIMATE UNIFICATION
Cape Antimatter
QUARK SEA
EXTRA DIMENSIONS ARCHIPELAGO
DARK ENERGY MAELSTROM
SEA OF THEORIES
STANDARD MODEL HARBOUR
KNOWN TERRITORY
Mount Einstein
Newton's Lawn
0
1 lightyear

The end

or maybe the beginning for you…