Particle Physics:
The history of the Universe written with 17 letters

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Introduction to Nuclear and Particle Physics course

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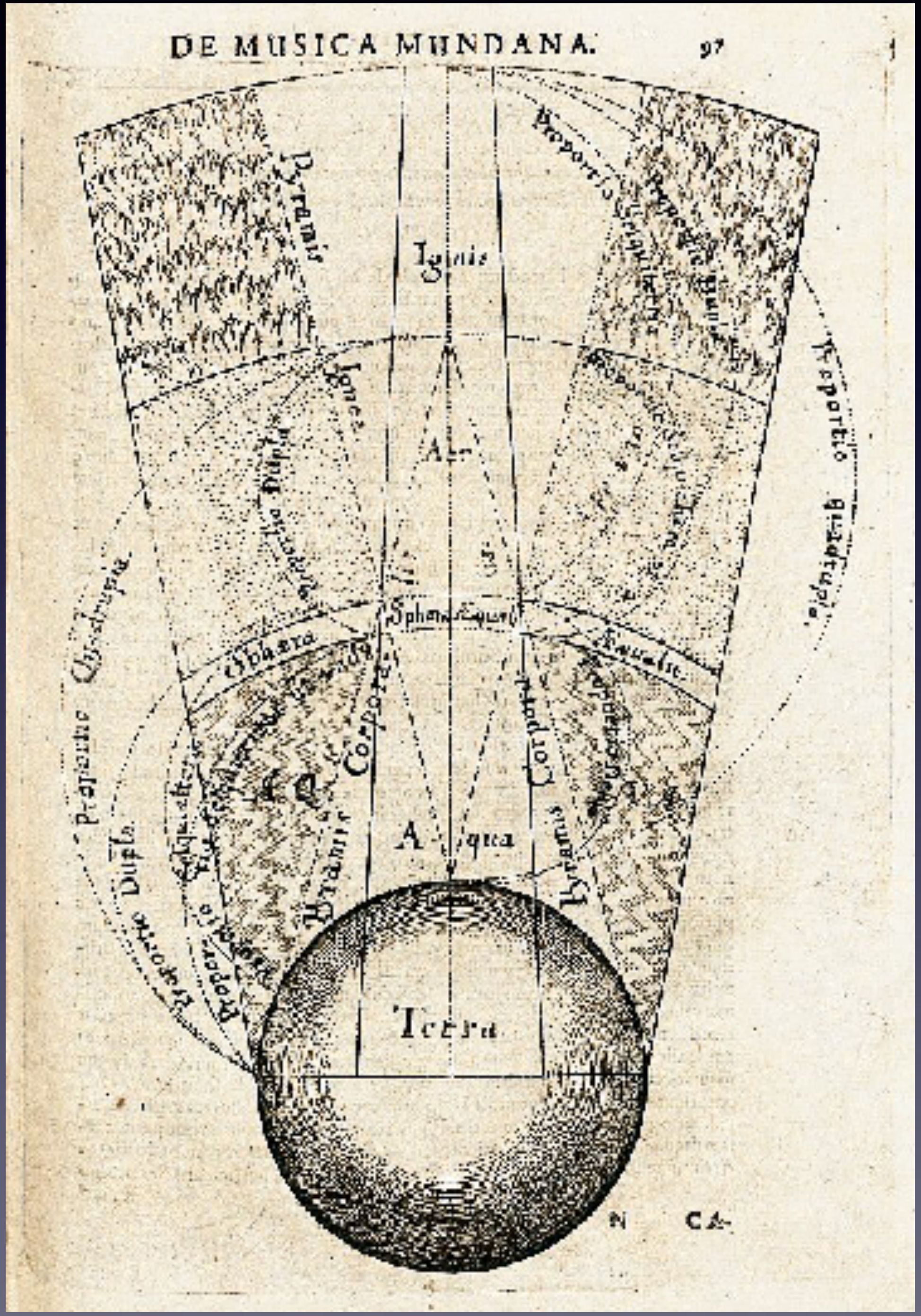
Outline

- Historical overview: the long quest for knowledge of the Cosmos
- The questions addressed by Particle Physics
- The current status of Particle Physics
- Frontiers in Particle Physics: state-of-the-art experiments and challenges

Brief history of human thinking about the Cosmos

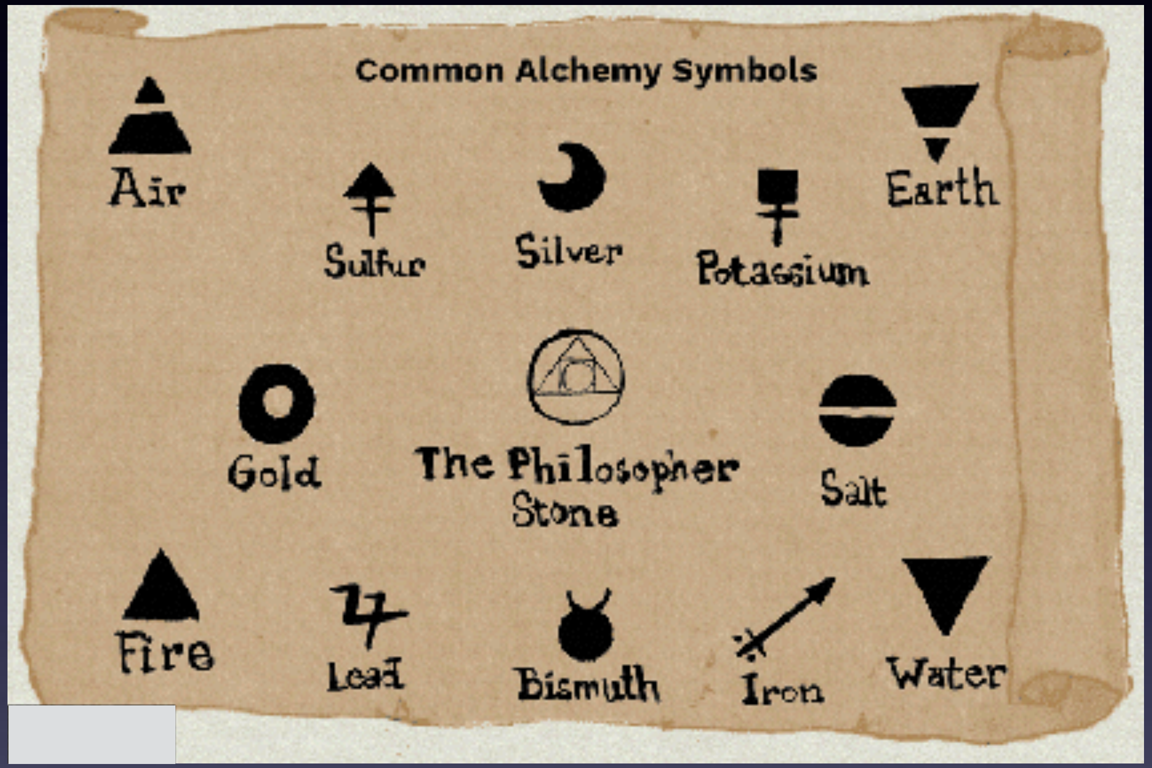
- ➢ Foundation of the "natural philosophy": greek pre-socratic philosophic schools and asian philosophies on the essence of Nature
  - ▻ Thales → water
  - ▻ Anaximander → the infinite
  - ▻ Anaximenes → air
  - ▻ Heraclitus → fire
  - ▻ Parmenides → the being
  - ▻ Empedocles → earth, water, air, fire
  - ▻ Anaxagoras → elements that can be indefinitely divided



- ➢ Introduction of the "particle" notion: the birth of the **atomic theory**
  - ▻ Democritus → individual tiny elements ("atoms") and vacuum

Brief history of human thinking about the Cosmos

- Aristotle's legacy in Medieval science → strong influence on both christian and islamic philosophy in Europe, Middle East, and North Africa
  - Alchemy: metamorphosis of elements
  - Astronomy: theory of celestial spheres
  - Reason in human perception:
    Nature can be understood by cause and deduction → "physical law"



Alchemy symbols of various substances

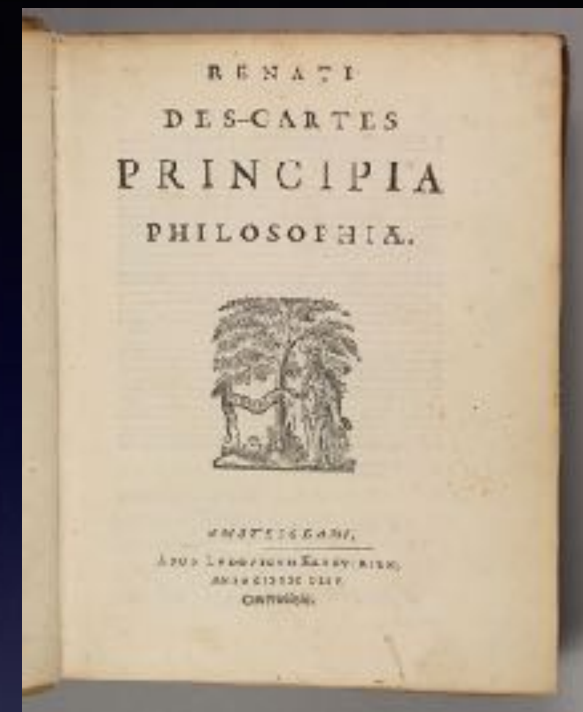
Aristotle:

"We think we know the cause of a thing when we can answer the question 'why?'"

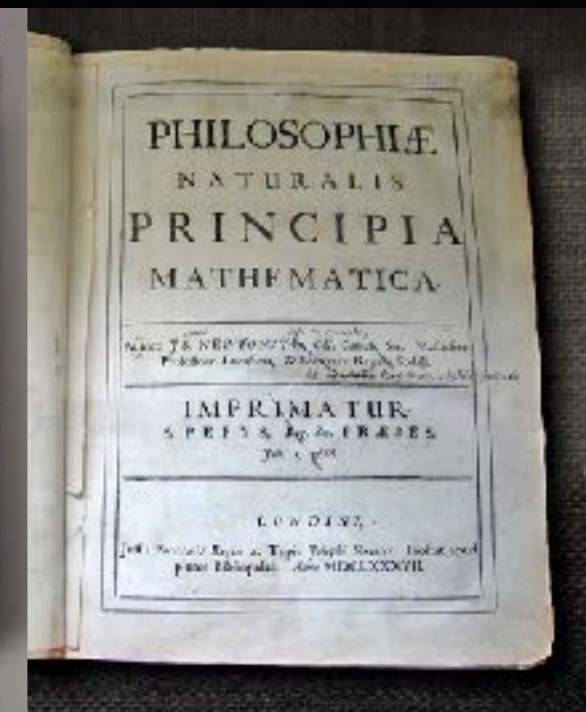
Brief history of human thinking about the Cosmos

Copernicus' helio-
centric Universe

Galileo showing Doge
his telescope



Descartes'
"principia"



Newton's
"principia"

- ➢ **Revision of natural philosophy in modern times: European Enlightenment**
  - ▻ **Empiricism → establish the concepts of "observation" and "experiment"**
  - ▻ **Rationalism → advance "physical law" beyond human perception**
  - ▻ **But Nature was still described with "passive" atoms → no "interaction" yet**

Brief history of human thinking about the Cosmos

Volta showing his battery to Napoleon

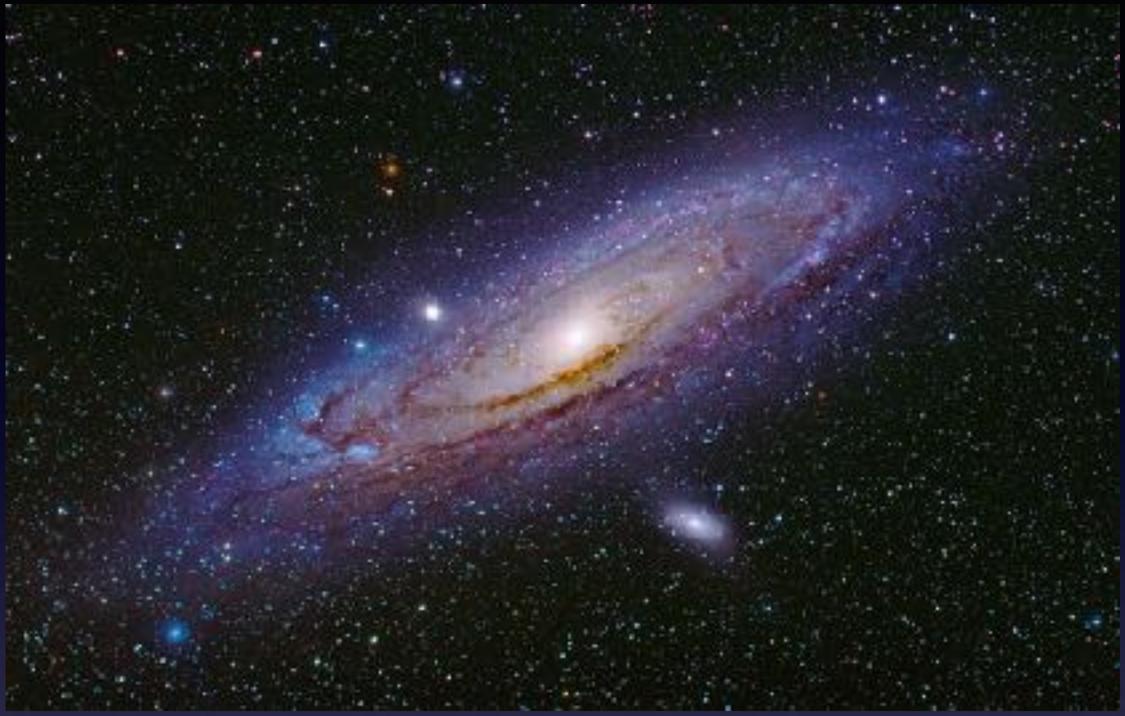
Oersted performing his experiment

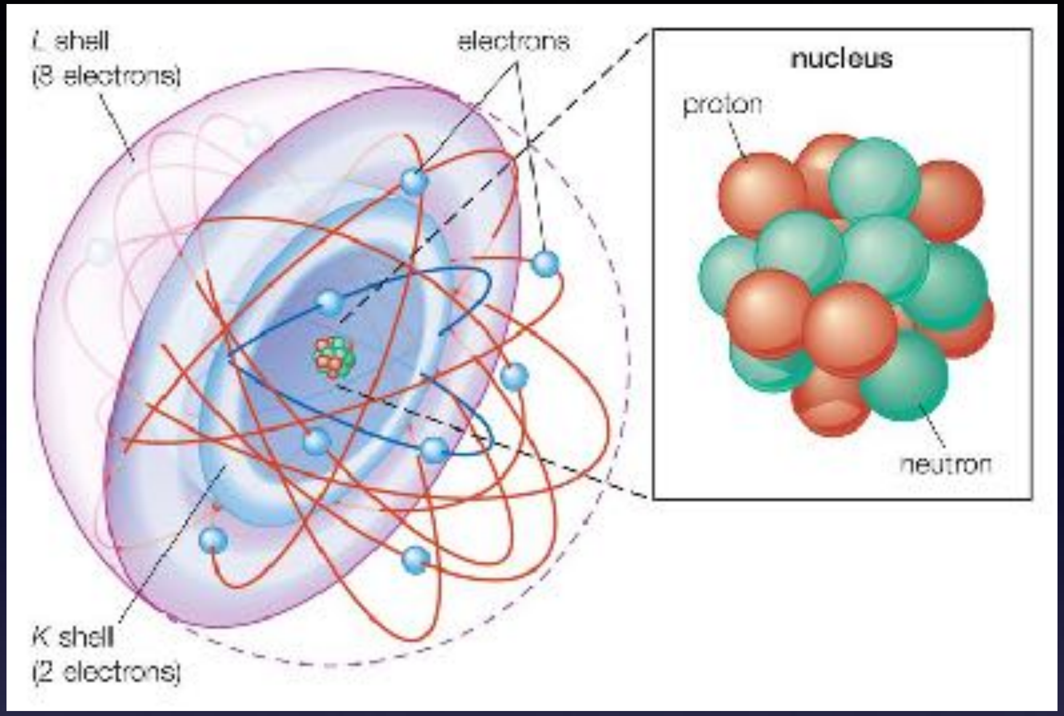
Prototype of Watt's steam engine

➢ **The 19th century: building "classical physics" — physical laws at the human scale**

- ▻ **Electricity and magnetism → fundamental interactions**
- ▻ **Thermodynamics → microscopic origin of macroscopic phenomena → revival of the atomic theory, but soon realised that the atoms are not really "atoms" (= individual)**

Brief history of human thinking about the Cosmos





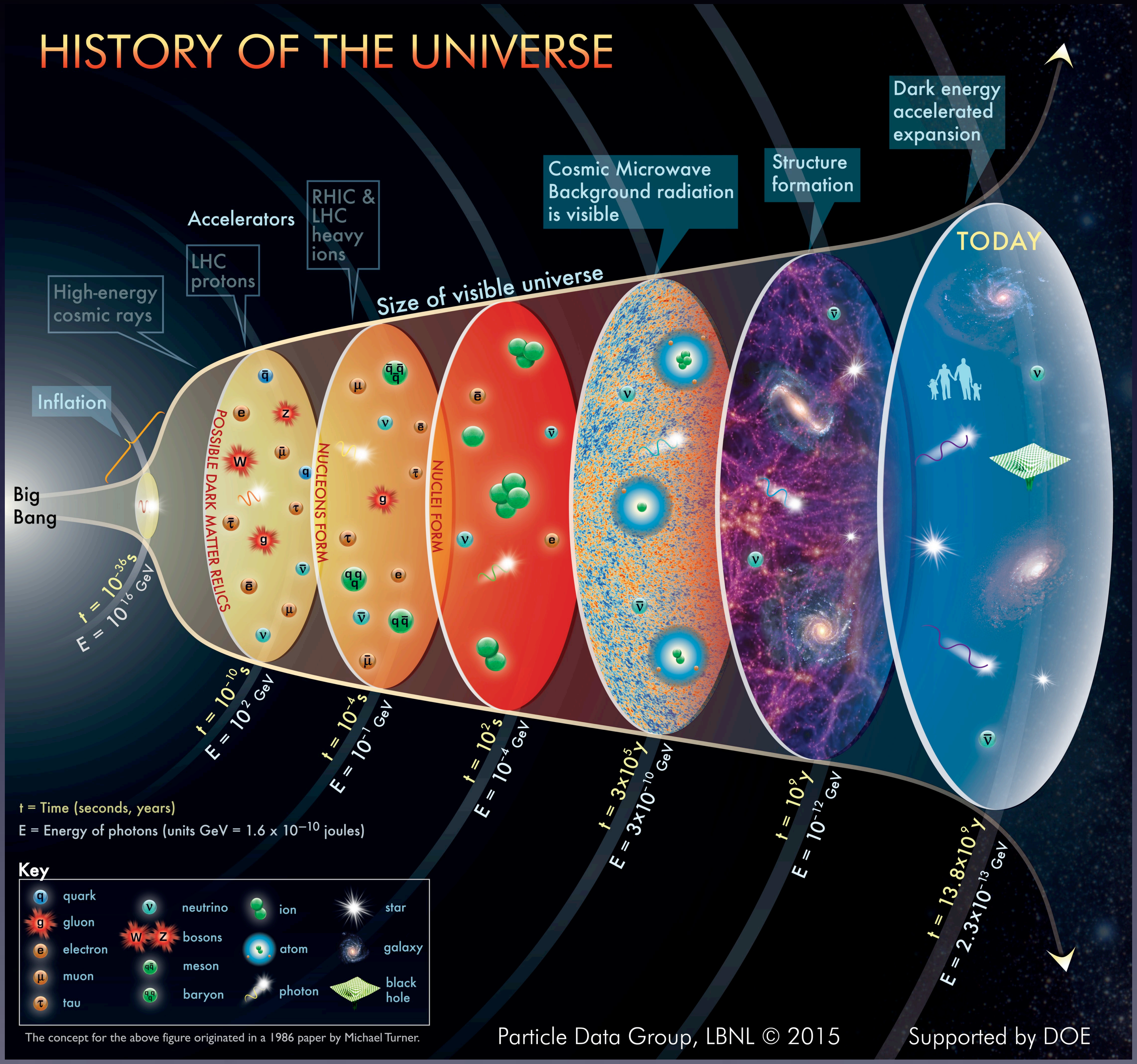
From galaxies…

…to atoms and nuclei

- **The 20th century: building the "modern physics" — physical laws at the Universe and (sub)atomic scales**
  - **Modern theory of gravity → describes motion in the Universe**
  - **Quantum mechanics → describes motion of subatomic particles**
  - **Discovery of the particle "zoo" → deep study of the structure and fundamental properties of matter**

Brief history of human thinking about the Cosmos

- ➢ The 21st century: searching for "new physics" — tracing the history of the Universe all the way back to its origin



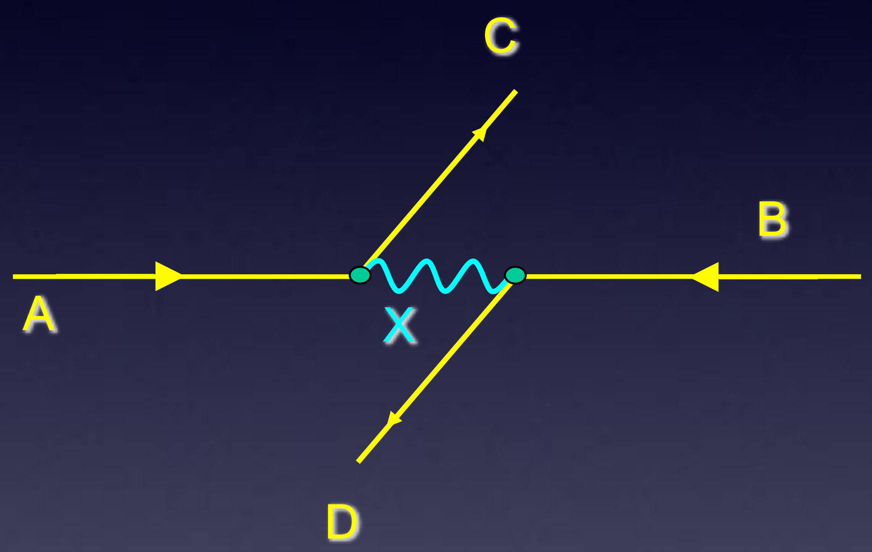
Requires a deep understanding of the fundamental elements of matter and of their interactions → particle physics

What is Particle Physics about

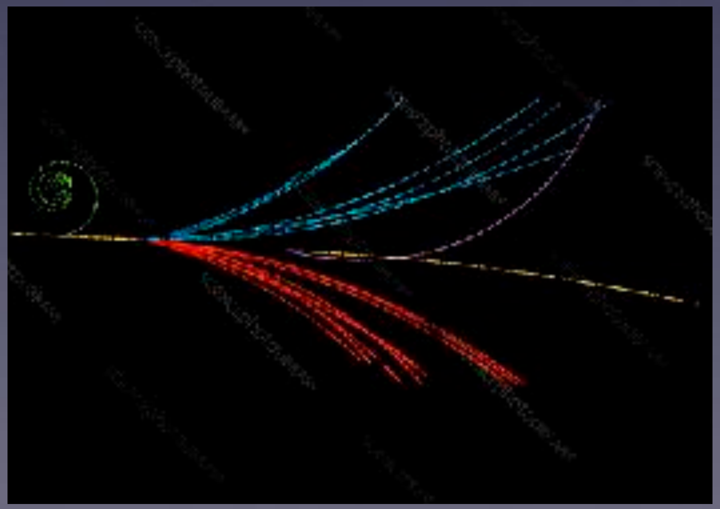
- ✓ **What is a particle:** object whose motion does not depend on its structure*, if any

- ✓ **What is an elementary particle:** a particle with no (known) structure

- ✓ **Fundamental interactions:** particles interact by exchanging other particles, called **"force carriers"**, for example two electrons interact by exchanging a photon



- ✓ Particles can decay: they are divided into **stable** ones (like the electron and the proton) and **unstable** ones (like the neutron) with **lifetimes** usually tiny fractions of a second


Production and decay of a Λ particle

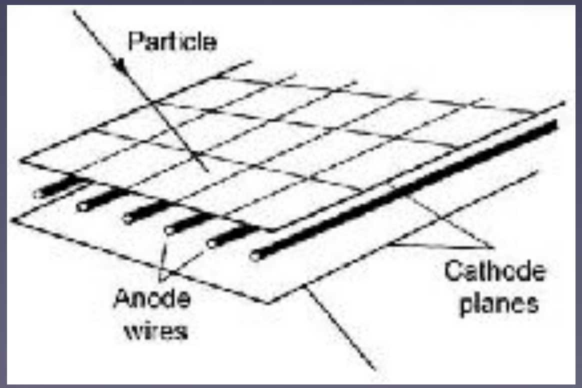
*structure: characteristics describing a spectrum of states of the object at rest

What is Particle Physics about

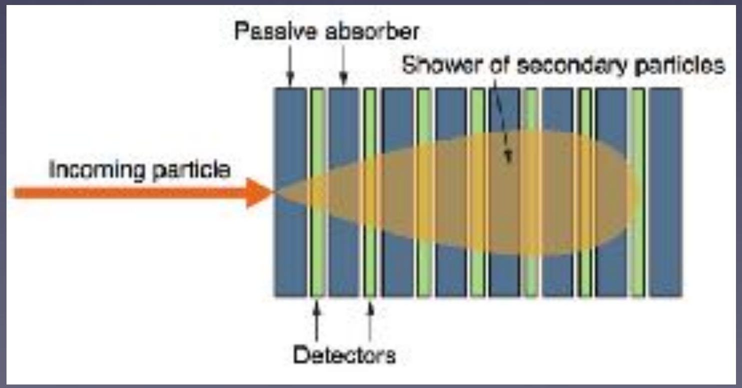
- ✓ **Matter particles have antiparticles (antimatter partners): “mirror reflections” with identical properties, except opposite charges, annihilate with matter particles**

- ✓ **Particles can be detected by tracing their interactions while traversing materials**
  - ❏ **Bubble chambers (1920-1980) → trajectories**
  - ❏ **Ionisation chambers → positions and times**
  - ❏ **Calorimeters → energies**
  - ❏ **Semiconductor pixels → positions and times**

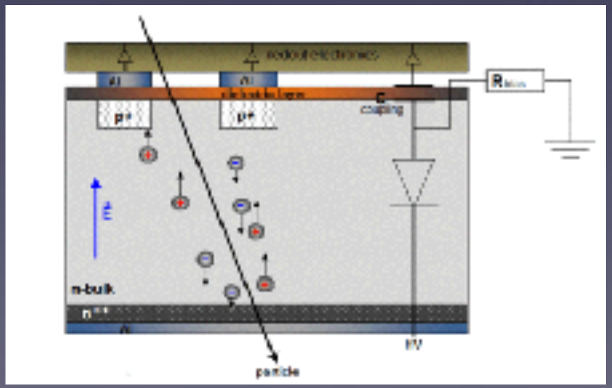
Bubble chamber



Ionisation chamber



Calorimeter



Semiconductor

What is Particle Physics about

✓ **The identity of a particle:**

mass

The energy of the particle at rest (having zero momentum)

requires special relativity

spin

The angular momentum of the particle at rest

requires quantum mechanics

charge(s)

The strength by which the particle interacts with other particles that "feel" the same fundamental interaction

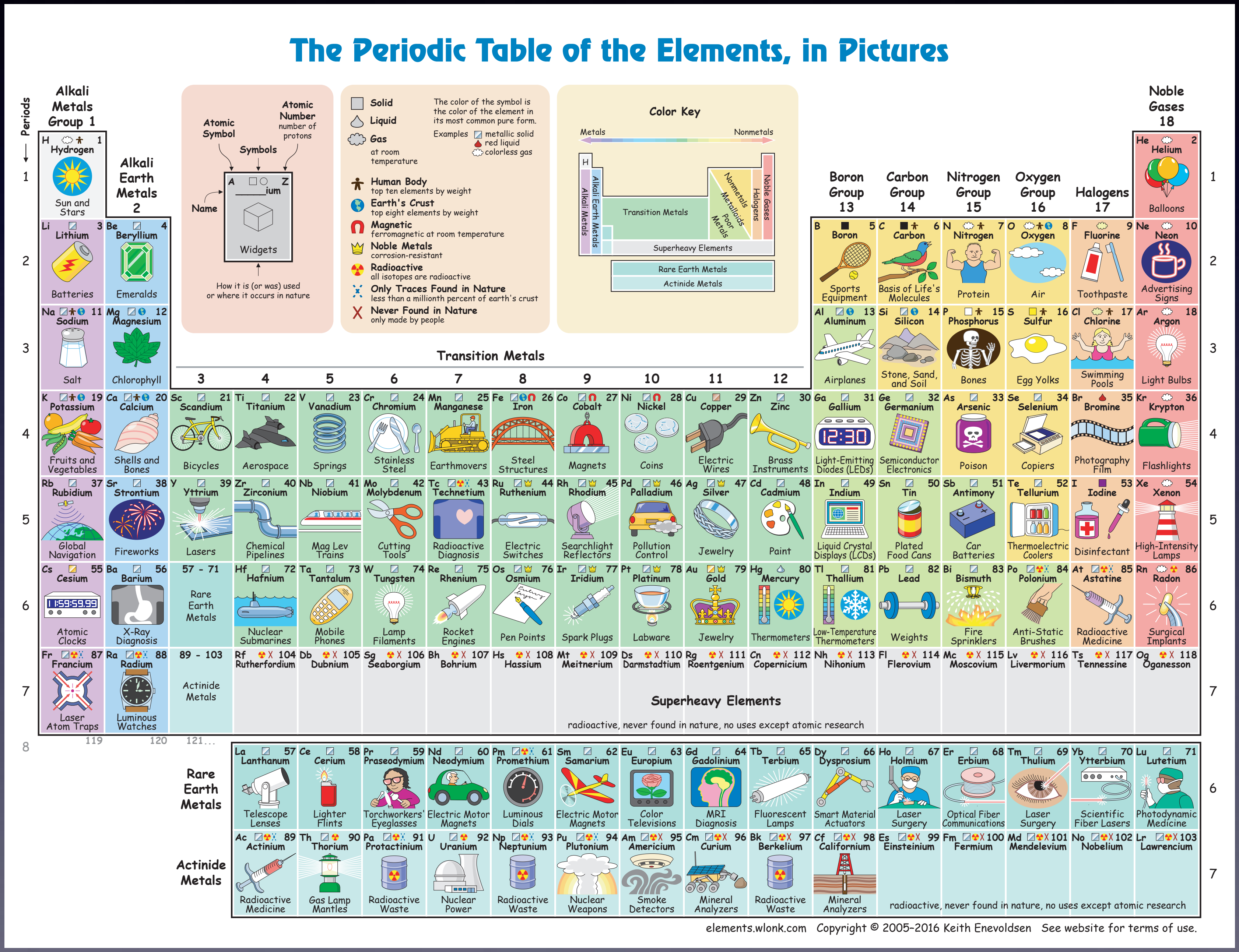
requires a "gauge" theory

✓ **How many distinct particle types exist (= what are the World's building blocks) ?**
→ the fundamental question of Particle Physics

✓ **Classifying particles by their properties reveals symmetries of the particle world**
→ understand particle interactions and composition of matter

Map of particles according to their properties: the paradigm of Mendeleev's Periodic Table

Chemical elements grouped in "families" by common properties

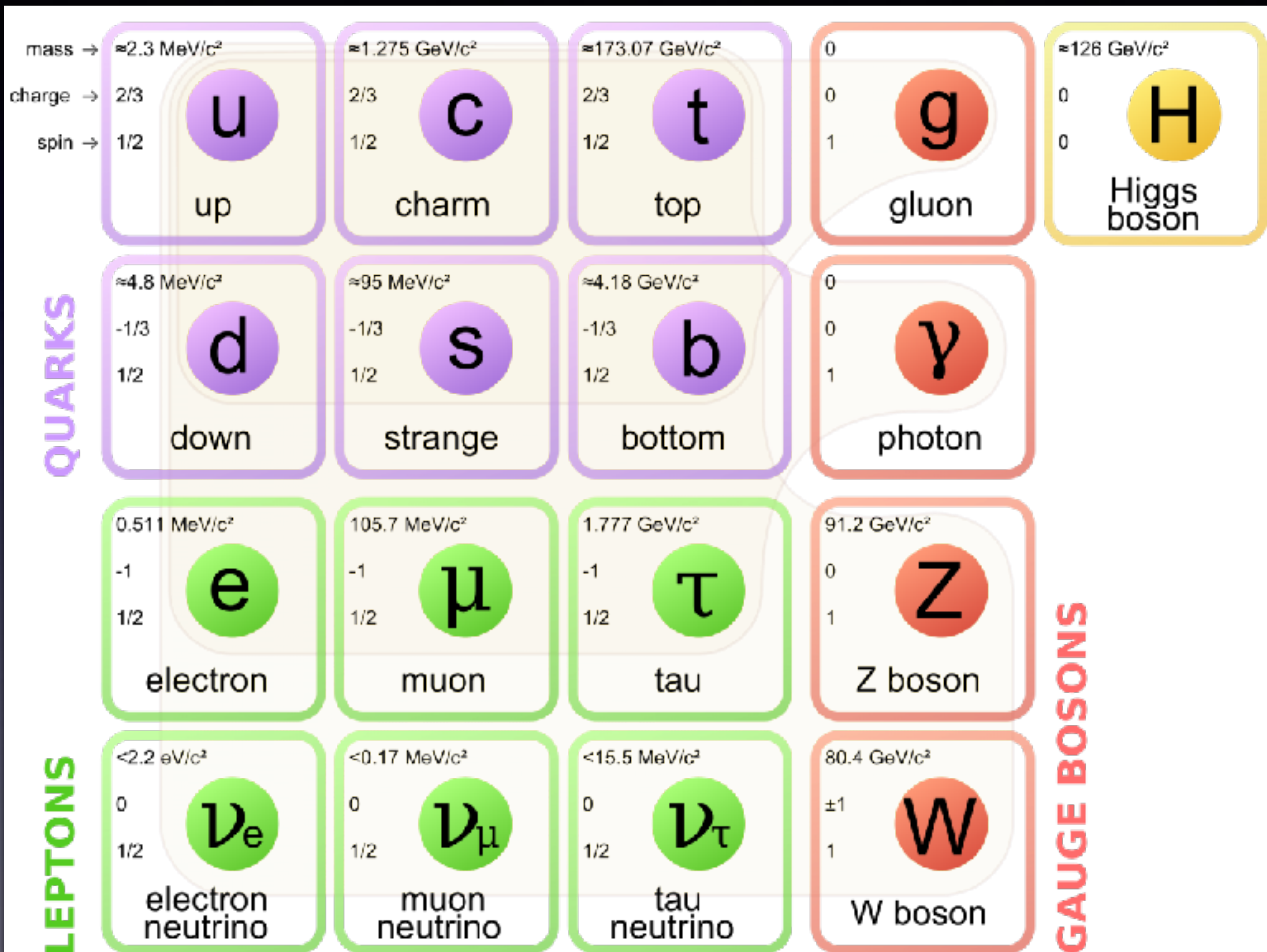


Underlying idea:

Just three types of particles (proton, neutron, and electron) suffice to explain all properties via quantum mechanics

Keeps expanding with new short-living elements

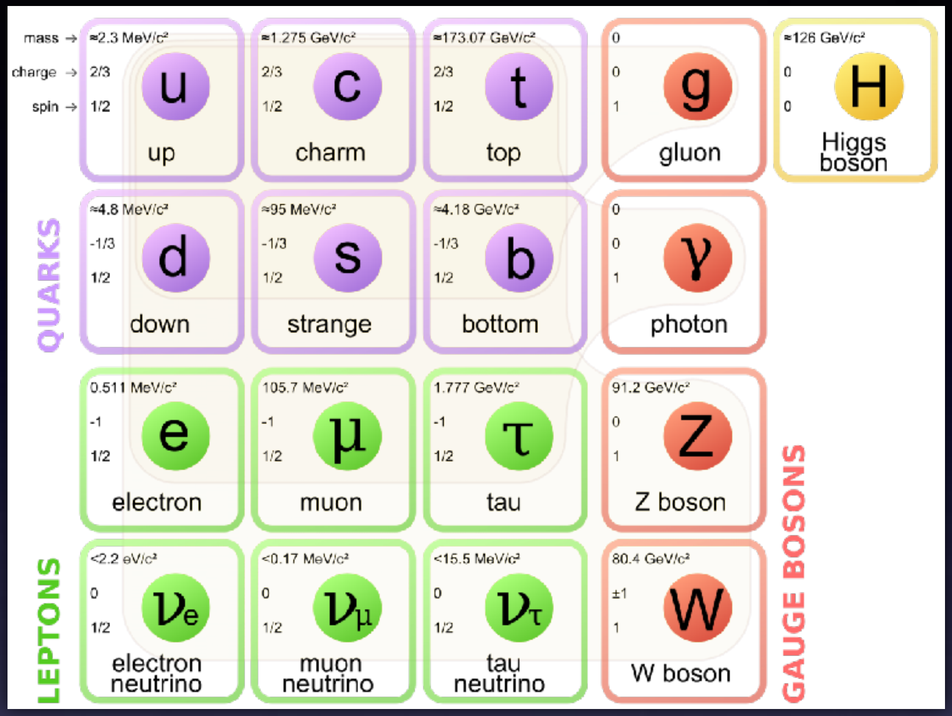
Periodic table of elementary particles: the Standard Model of Particle Physics

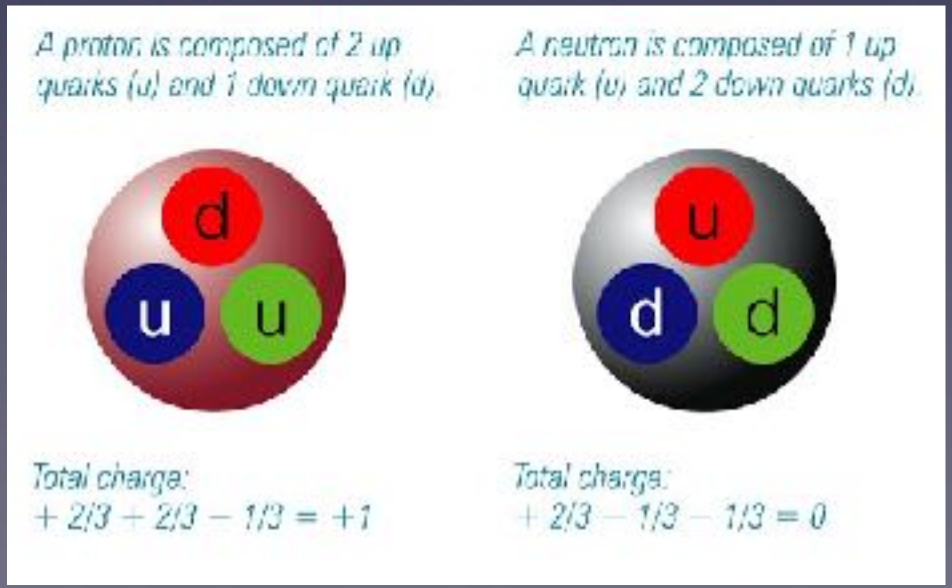


It takes much more than just three types of particles to explain everything…

The Standard Model in a nutshell

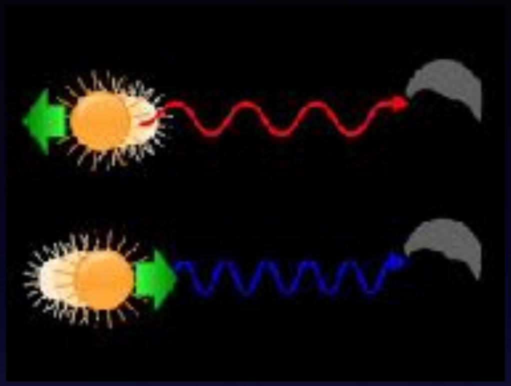
- ✦ Three “families” or “generations” of particles building up matter (“fermions” with spin 1/2)
- ✦ Fourth column shows particles-“messengers” of interactions (“bosons” with spin 1)
- ✦ Three interactions: “strong”, building nuclear structures, electromagnetic, building atomic and molecular structures, and “weak”, causing particle decays—but not gravity, responsible for astronomical structures
- ✦ One particle interacting with the others to give them mass (the “Higgs boson” with spin 0)
- ✦ Building matter from elementary particles → the Quark Model
- ✦ Is that all ?





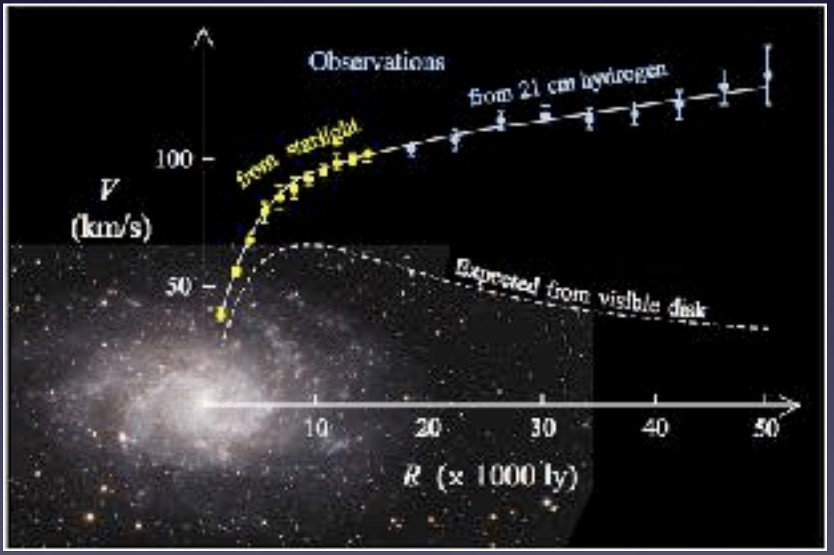
Looking back in the Universe: how well does the Standard Model describe it?

- Cosmological data show that the Universe came to be from a "Big Bang" of energy turning to equal amounts of matter and antimatter



- But then why is the Universe all made of matter? Where did antimatter go?

- Cosmological data also show that the Universe contains 4-5 times more mass than the visible mass



- Then what is the invisible matter ("dark matter") made of?

- Cosmological data additionally show that the Universe is expanding at an accelerating rate

- But gravity should decelerate the expansion, so what force ("dark energy") causes the acceleration?

More questions about the Standard Model: is it self-consistent?

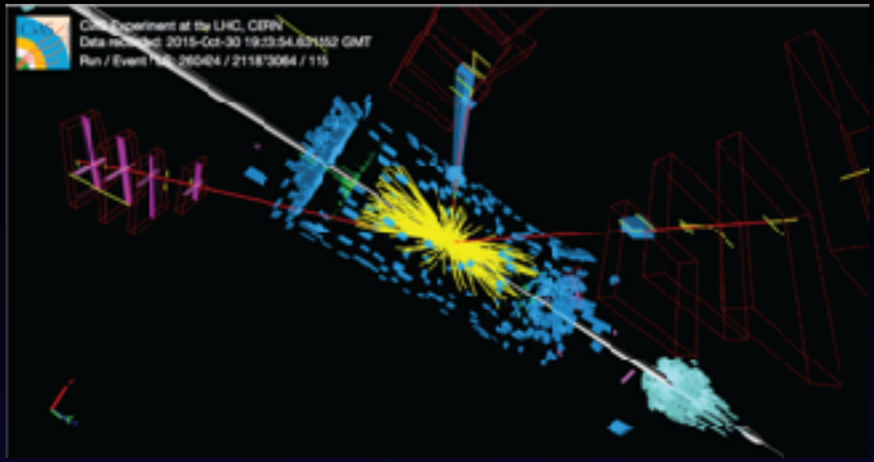
- ☞ What about incorporating gravity? It is by far the weakest interaction, but we need a particle-based theory of it to describe the interior of black holes (regions of space and time where gravity binds everything without escape)

- ☞ Putting interactions with all particles together, the Standard Model predicts an enormous Higgs boson mass, unless a miraculous cancellation of those interactions occurs to bring it down to the measured mass

- ☞ The Standard Model postulates that the neutrinos are massless, but experiments have proven that they have finite (albeit tiny) masses

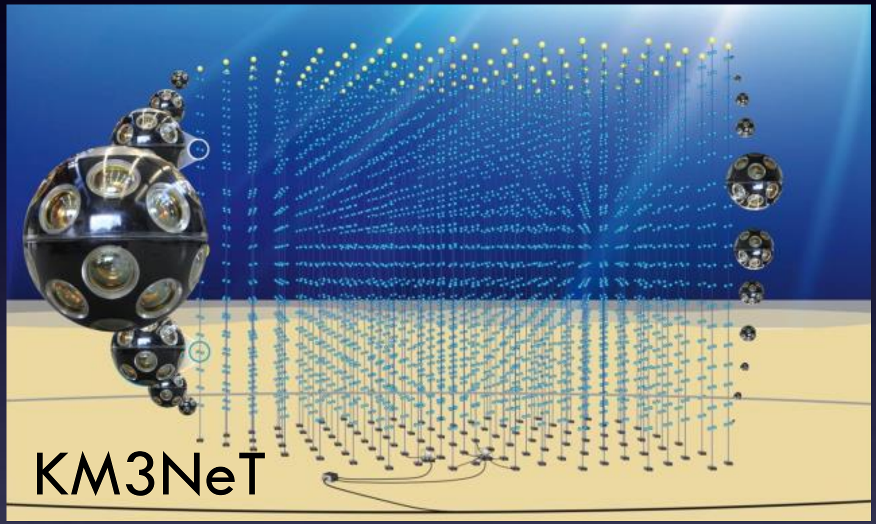
- ☞ For all these reasons, it is believed that the Standard Model is an "effective" theory, applicable only to the energy scales that we have so far explored, i.e. a limit of a deeper fundamental theory that has yet to be discovered

Searches for new physics beyond the Standard Model



Searches with particle colliders: the highest energies probe the shortest distances

Searches with large detectors: maximise the chance of elusive particles to reveal themselves



Searches via high-precision measurements of particle properties: look for the Standard Model accuracy limit

Searches using astro-particles: the Universe provides everything that can be searched for

Colliders: direct probes of the shortest distances

- The colliders accelerate two oppositely moving charged particle beams which then collide at selected beam extraction point(s), giving rise to the highest-energy events humankind can produce in the laboratory

- Quantum mechanics interprets events with very **high energies** as processes occurring in very **short times** (or distances, in relativistic terms), revealing the existence and the nature of all particles involved in these processes

- Beams can be formed with **particles**, as in proton-proton or ion-ion colliders, or with **antiparticles**, as in proton-antiproton or electron-positron colliders, and can be of different type, as in electron-proton or electron-ion colliders

- By probing shorter and shorter times, or distances, the colliders eventually reproduce the conditions of the Universe at the beginning of time and thus shed light on the unresolved mysteries of its creation

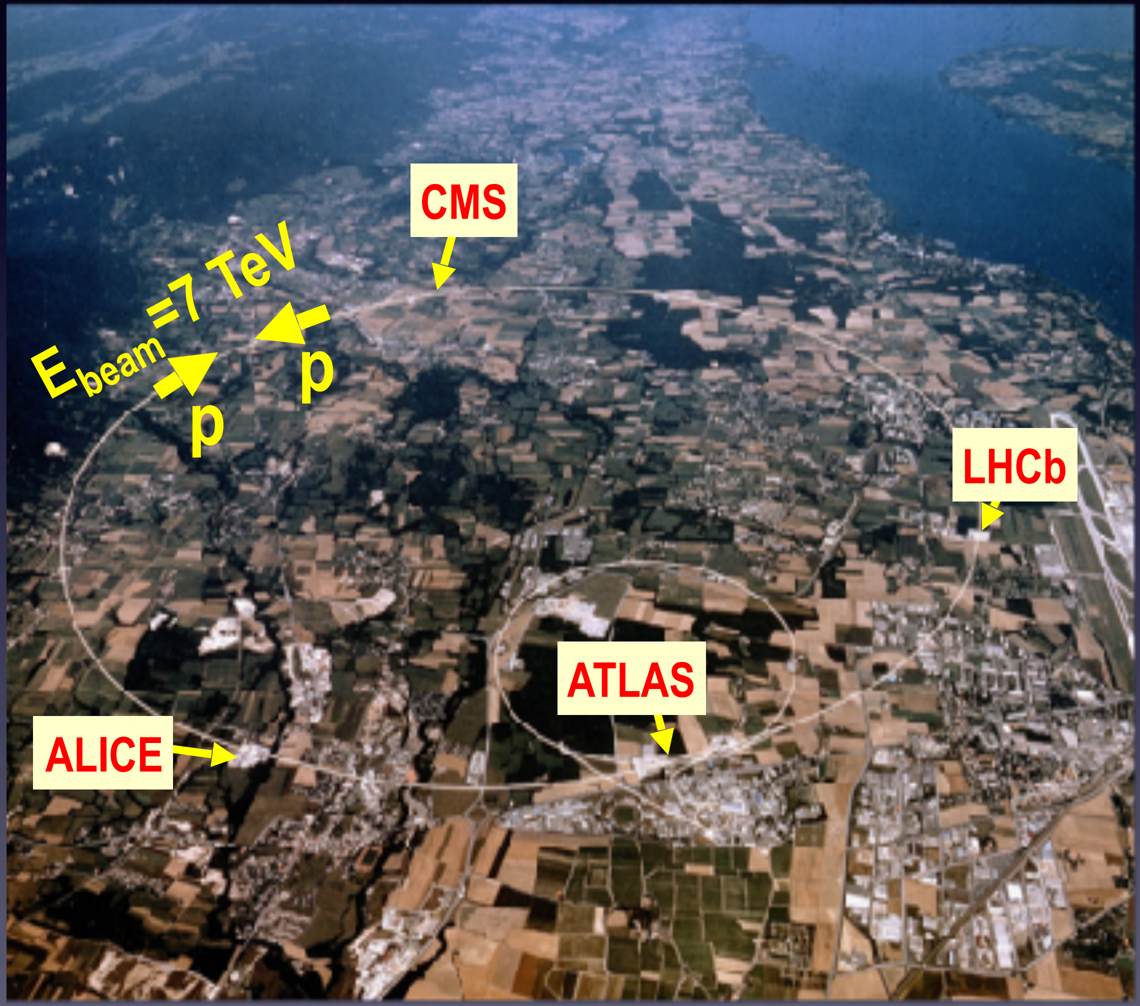
The Large Hadron Collider (LHC) at CERN

- The most powerful collider built so far, located in Geneva, Switzerland

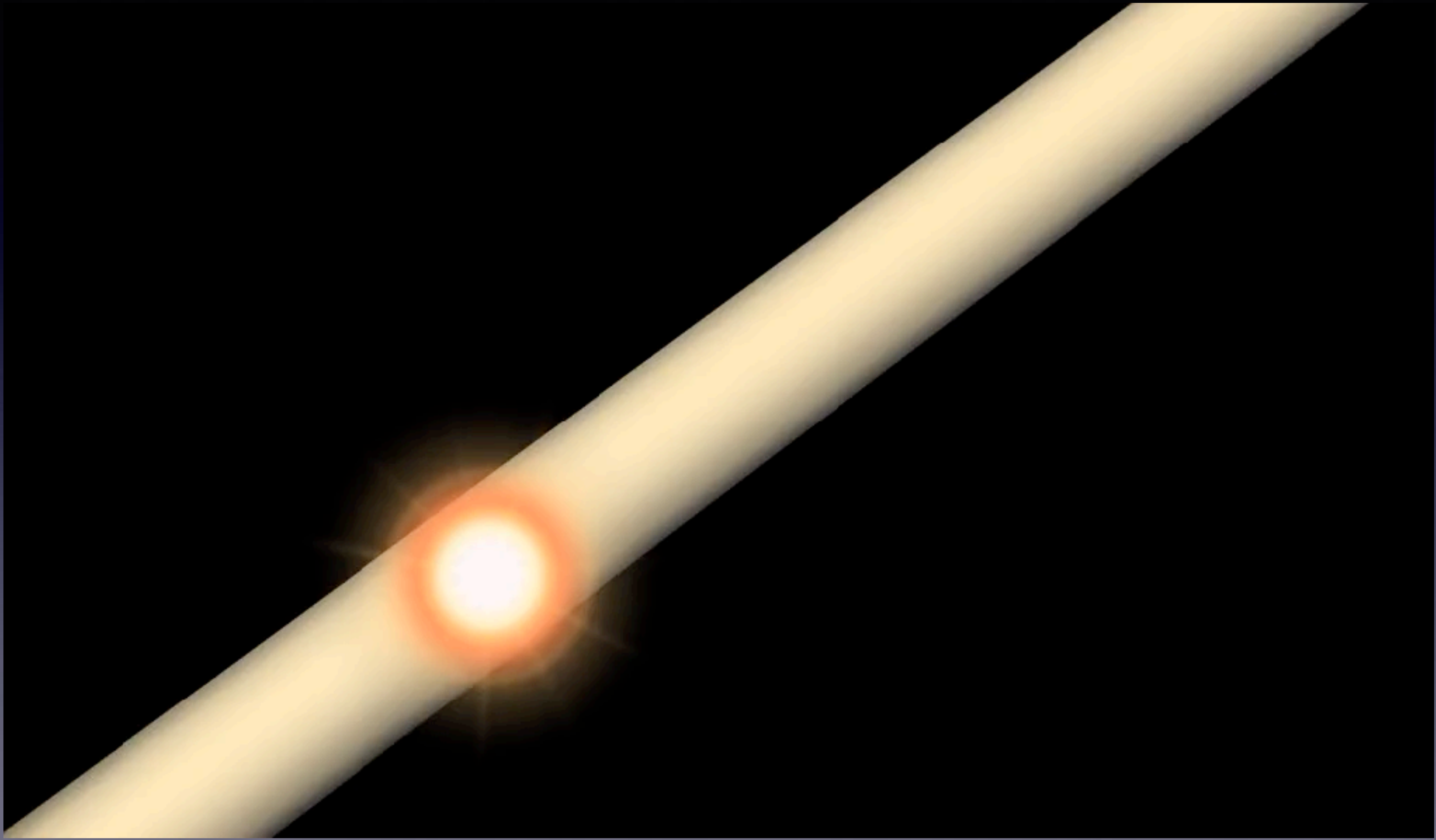
- Accelerates protons at energies up to 7000 higher than the proton mass

- The place of discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments

- Can also accelerate heavy ions at energies per nucleon up to 5000 times higher than the proton mass, in a wide range of atomic numbers



The Large Hadron Collider (LHC) at CERN



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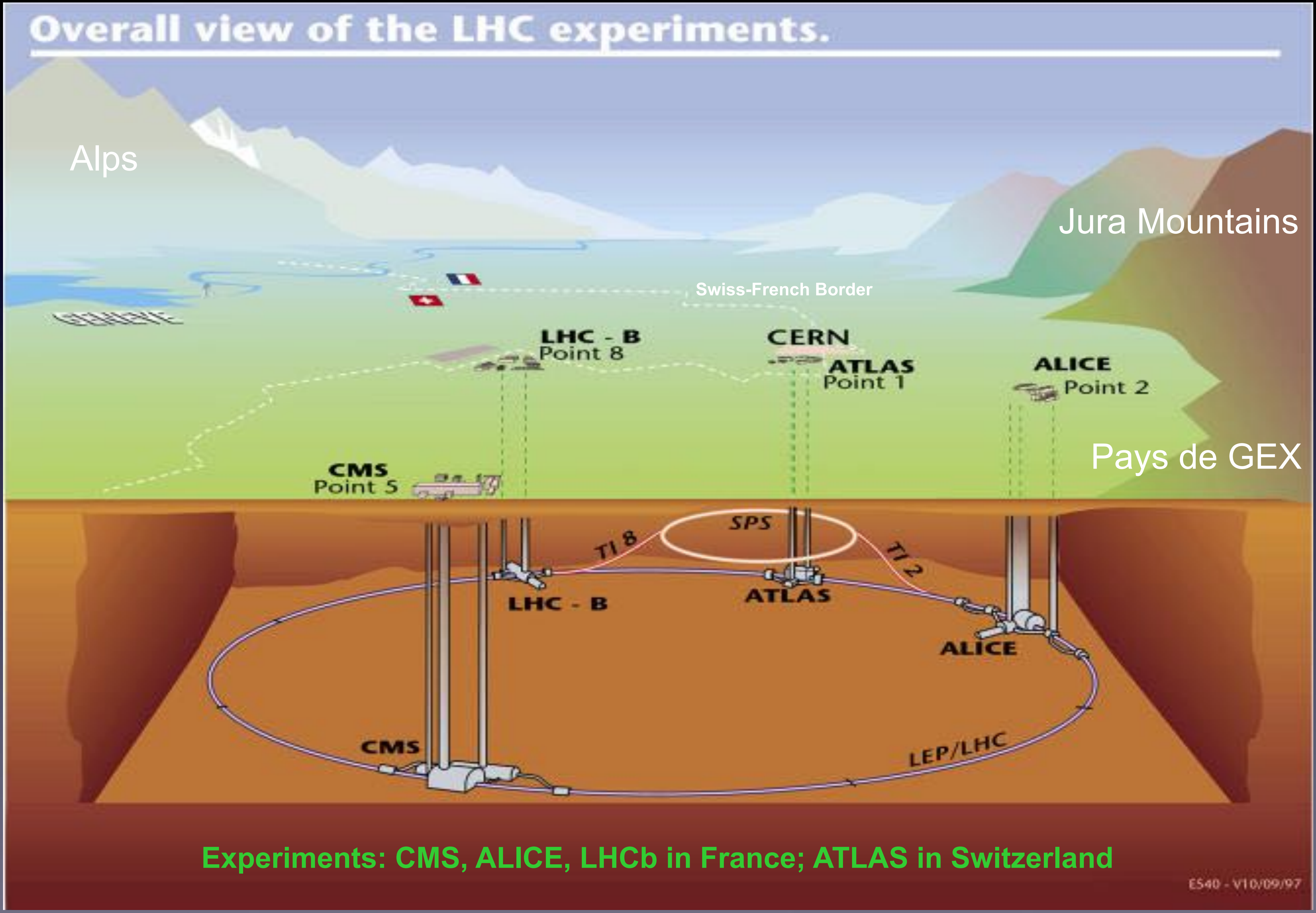
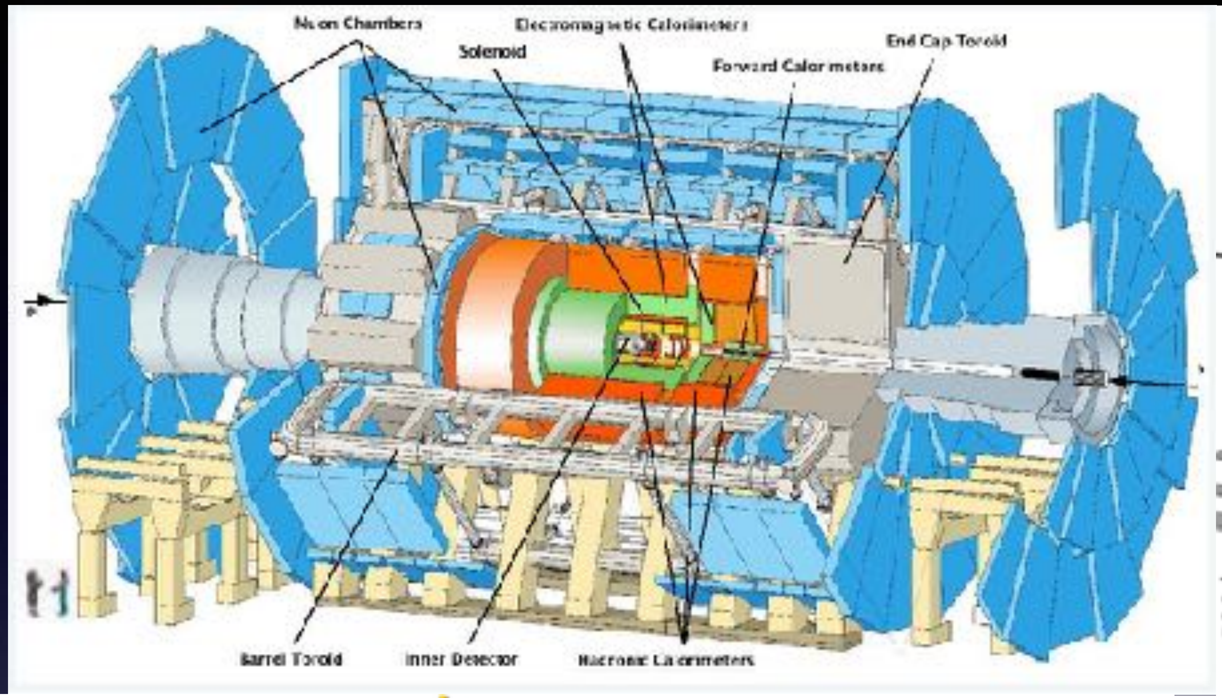
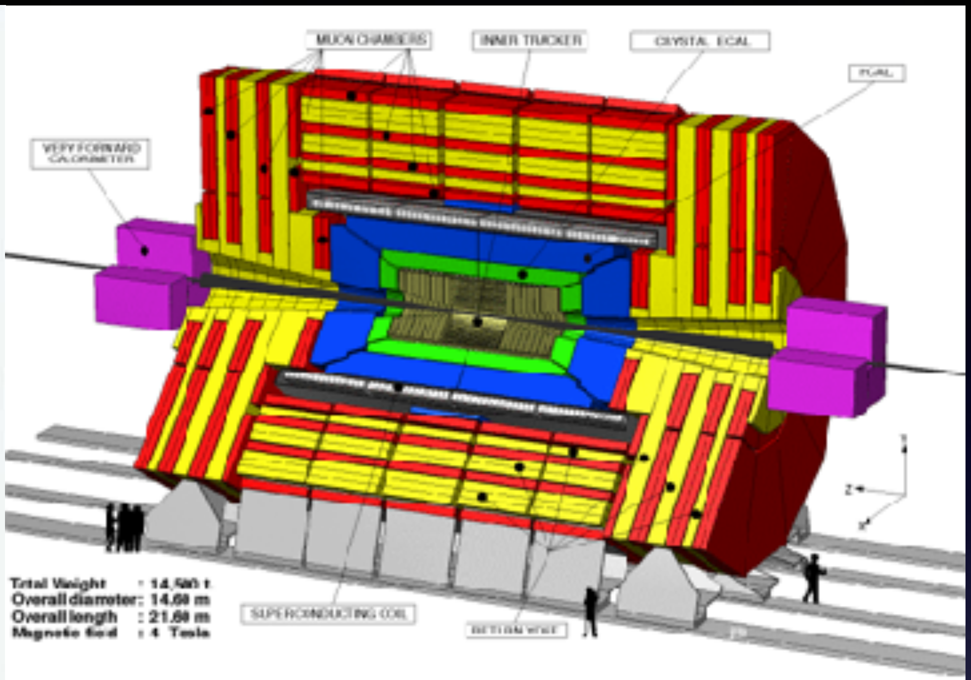


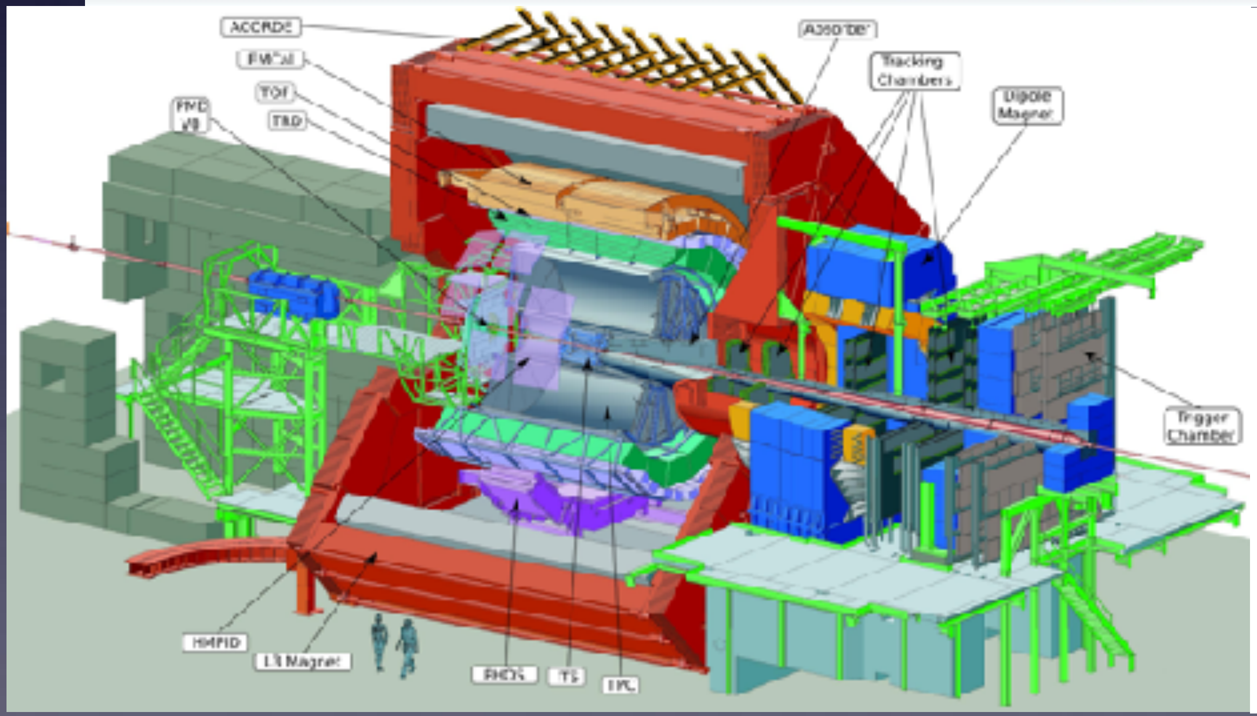
The Large Hadron Collider (LHC) at CERN

ATLAS

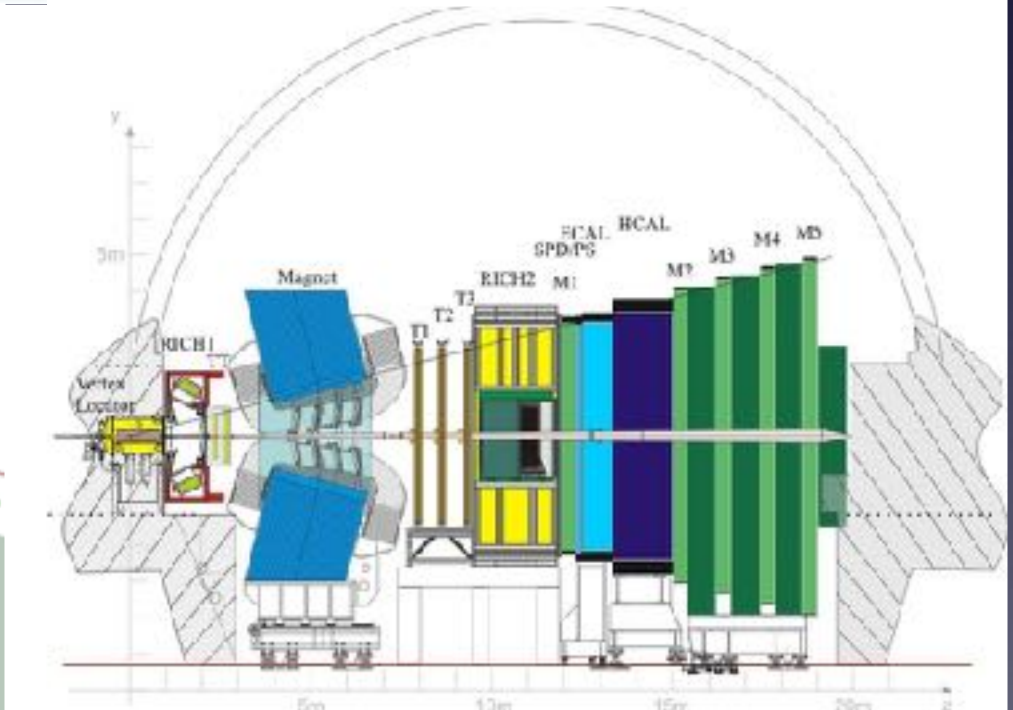


CMS





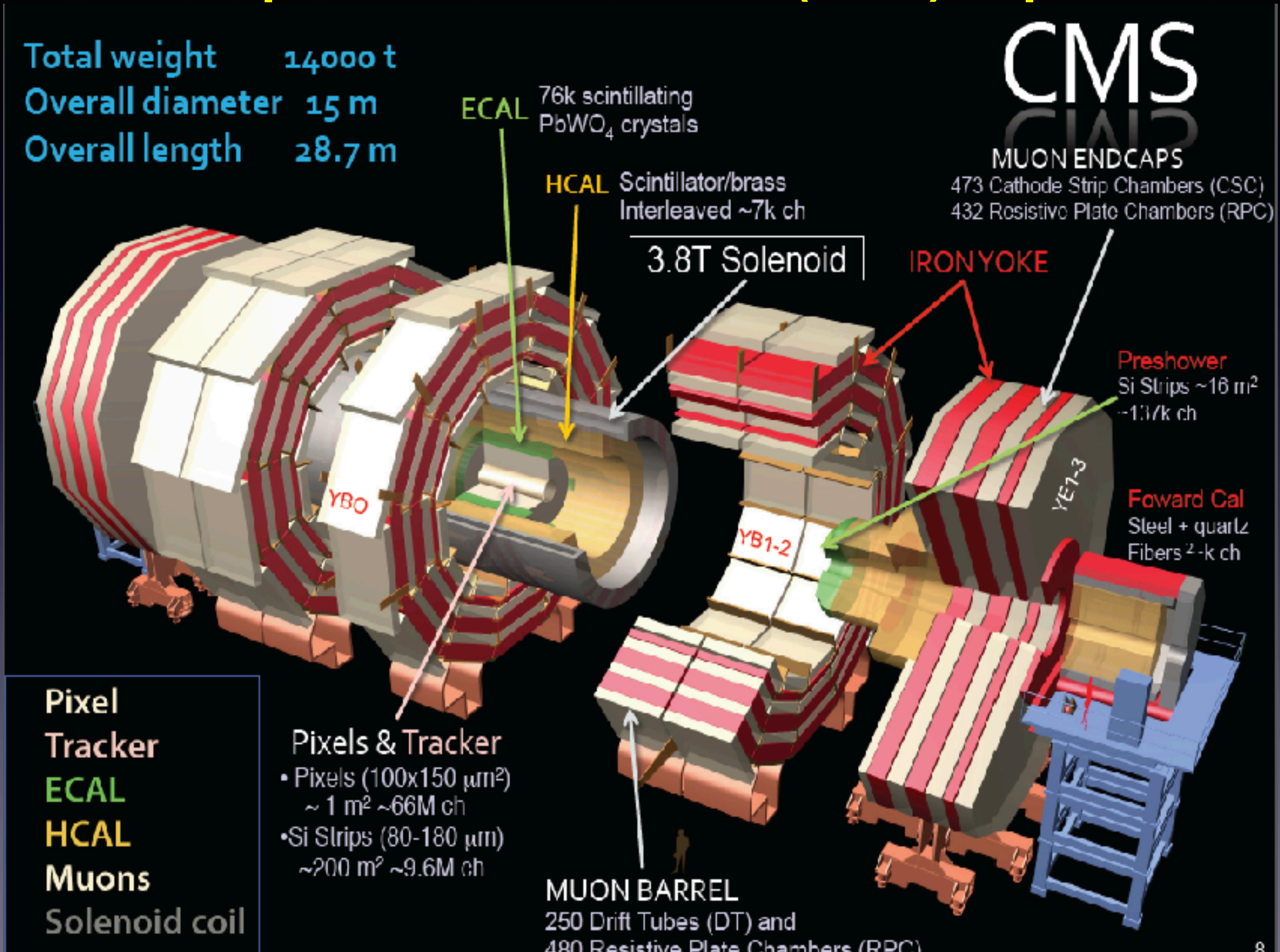
ALICE



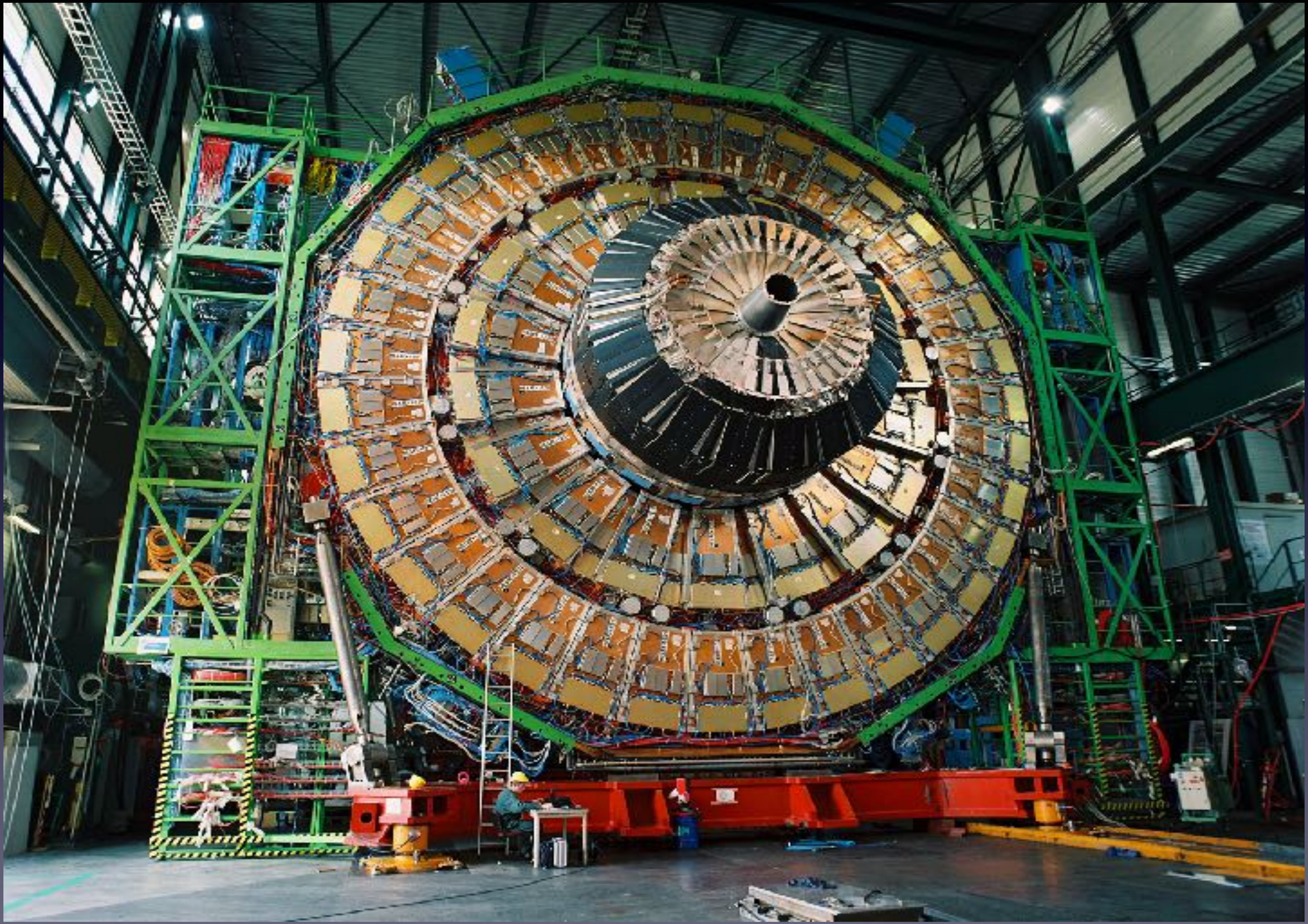
LHCb

- ✳ **ATLAS and CMS: of general purpose, detect all particles except neutrinos**
- ✳ **ALICE and LHCb: specialised in the physics of strongly interacting particles**

The Compact Muon Solenoid (CMS) experiment



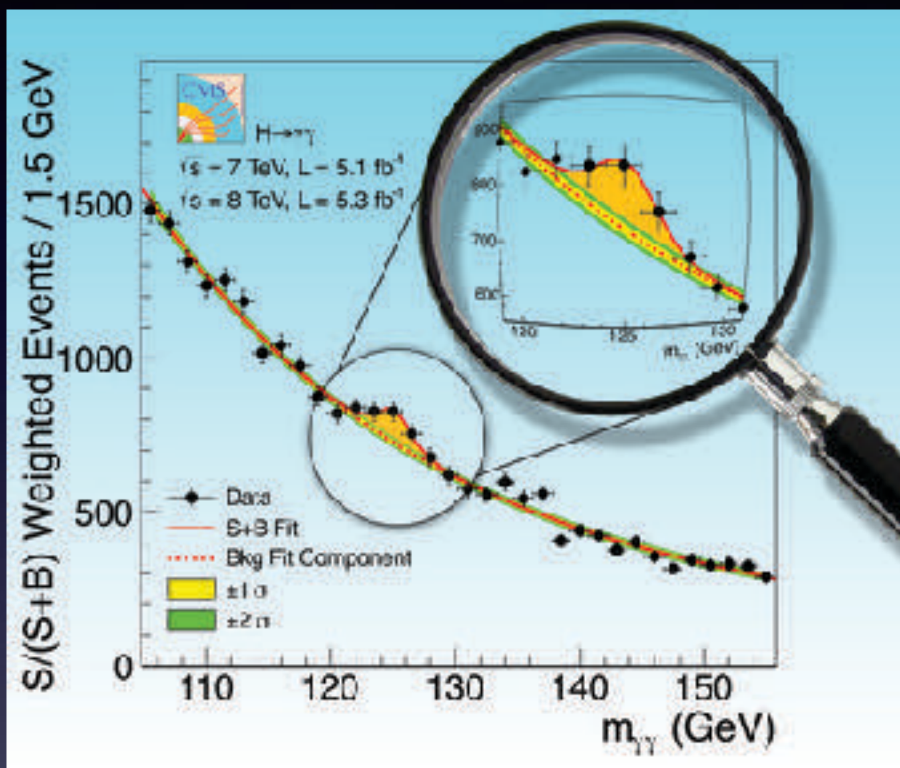
The Compact Muon Solenoid (CMS) experiment



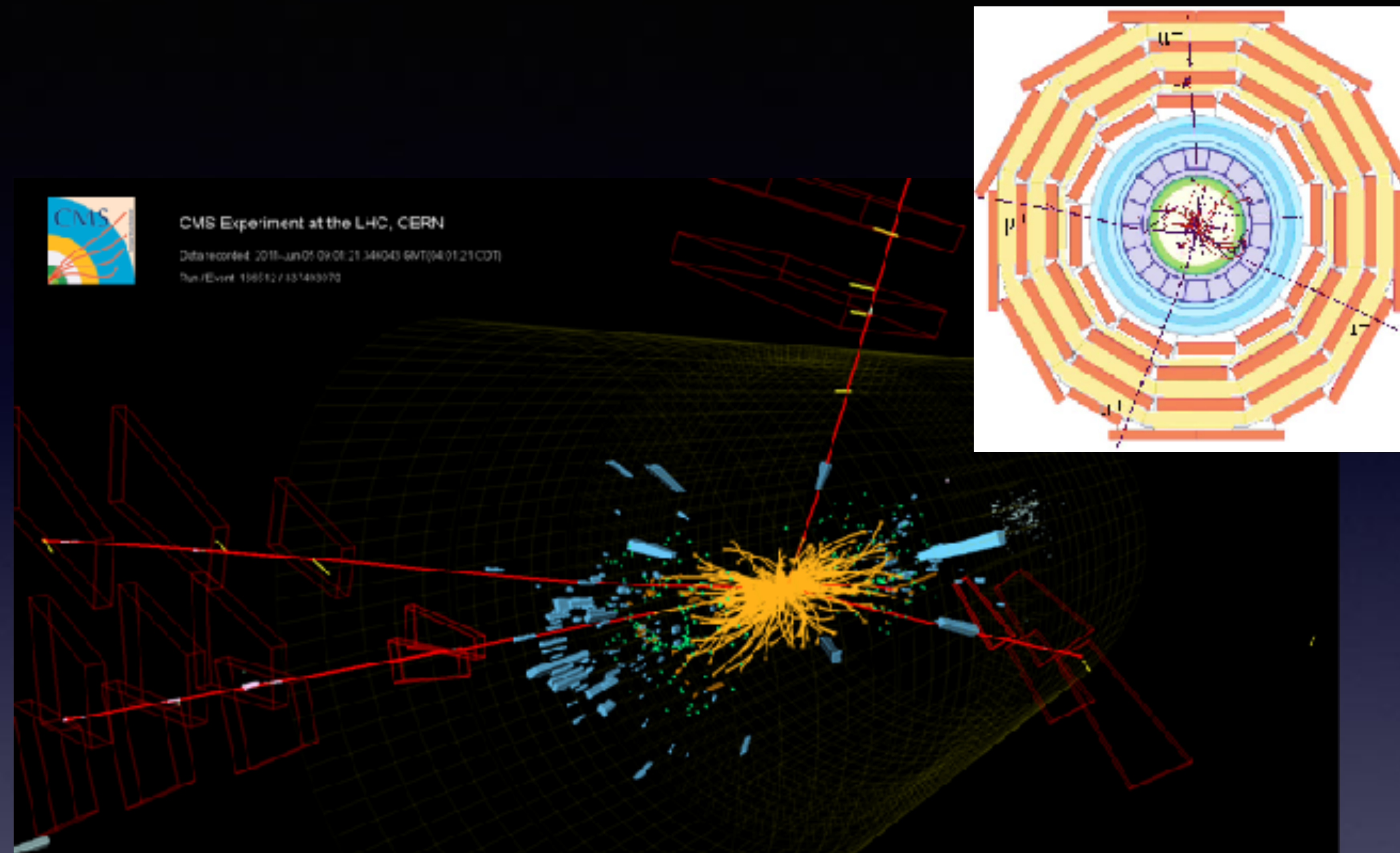
- All detector components were installed in the surface hall and then CMS was downloaded into the pit at Point 5

The Compact Muon Solenoid (CMS) experiment

Doing physics with CMS



The mass spectrum of photon pairs in CMS



A possible Higgs boson decaying to four muons in CMS

- ✳ **Very sophisticated algorithms are required to select and fully reconstruct collision events of interest**
- ✳ **Further sophisticated algorithms, specialised to the searched physics topics, are required to analyse the acquired data and extract the desired information**
- ✳ **An enormous amount of computing resources is needed to support data collection and analyses**

Neutrinos: physics beyond the Standard Model

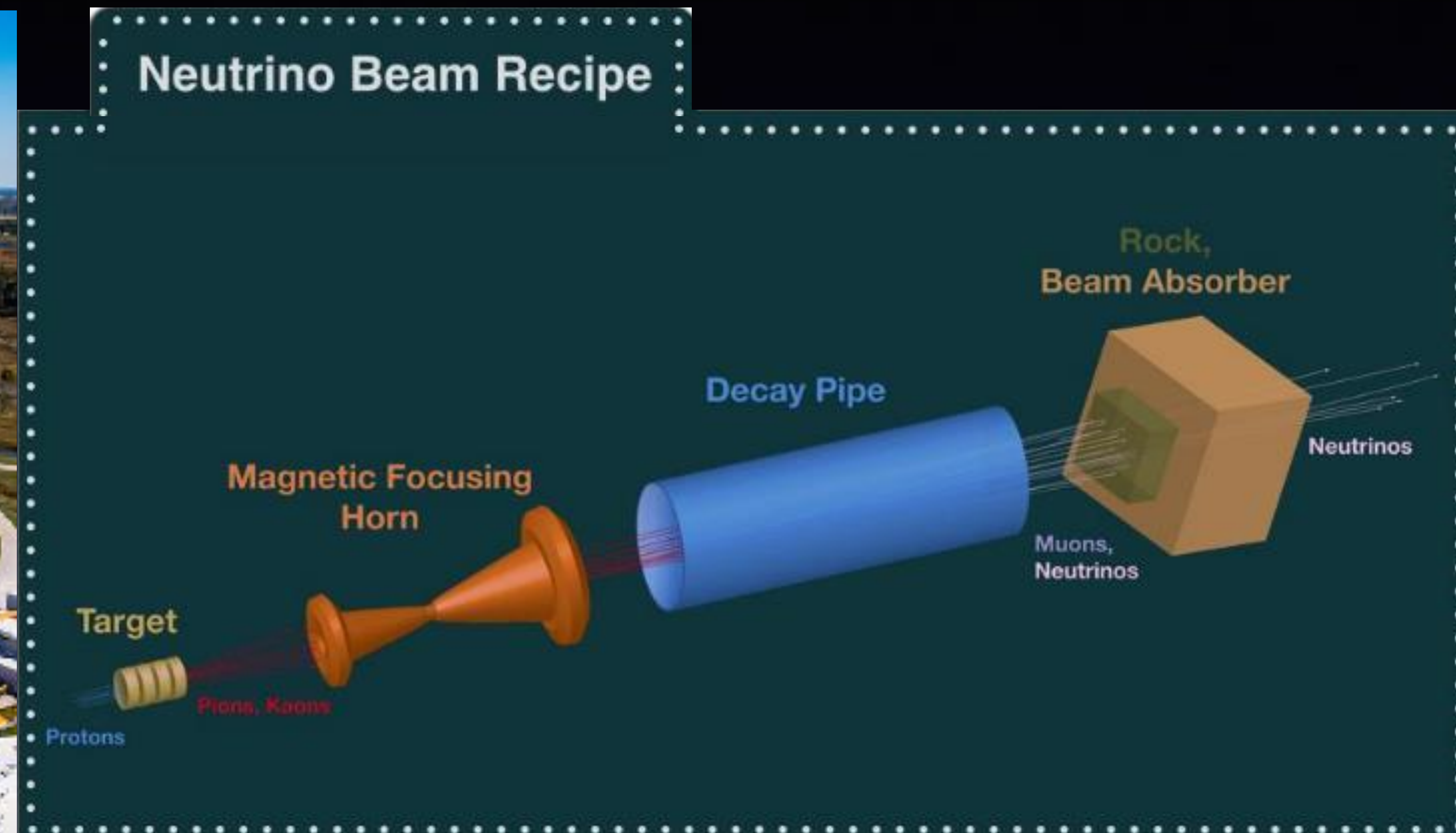
- Neutrinos are **the most abundant** known matter particles in the Universe, but they interact with other particles only via the weak interaction, thus making their study very difficult

- They were postulated by Wolfgang Pauli in 1930 to conserve momentum in measurements of radioactive decays of unstable nuclei

- They come in three "**flavours**", associated with the three types of charged leptons: ν_e is the partner of the electron, ν_μ is the partner of the muon and ν_τ is the partner of the tau lepton

- The Standard Model postulates them massless, but numerous experiments over the last three decades have shown, via observations of "**oscillations**" between different neutrino flavours, that they definitely have tiny masses (yet unknown, but thousands of times smaller than their charged lepton partners)

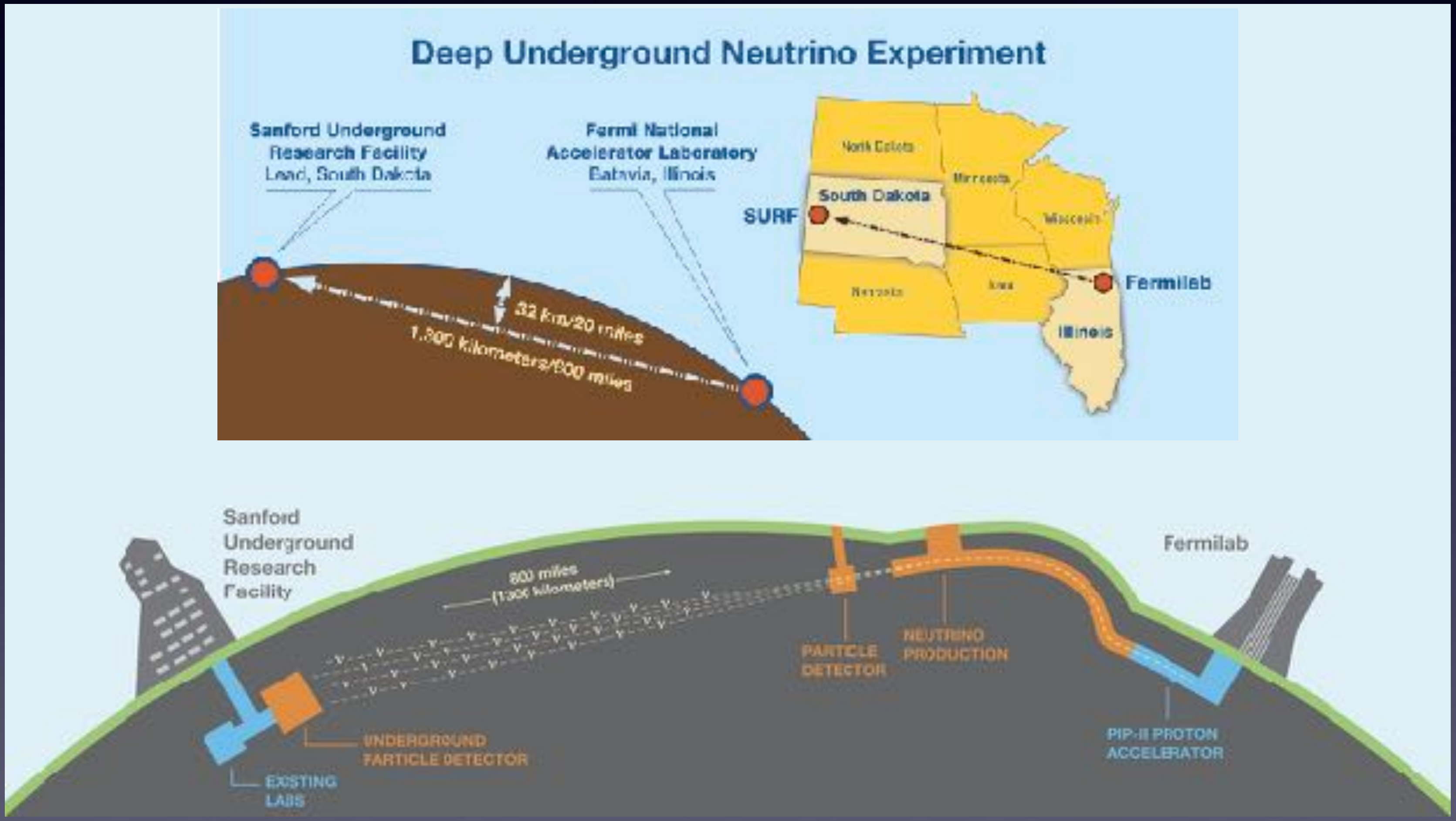
The Deep Underground Neutrino Experiment (DUNE) at Fermilab



- DUNE, the most ambitious experiment for the neutrino study, is being built at the US **Fermi National Accelerator Laboratory** (Fermilab) near Chicago
- It aims to measure all fundamental properties of neutrinos, including their masses and “flavour-mixing” parameters controlling the transition rates between different neutrino flavours
- These measurements can shed light on the mystery of matter-antimatter asymmetry in the Universe

The Deep Underground Neutrino Experiment (DUNE) at Fermilab

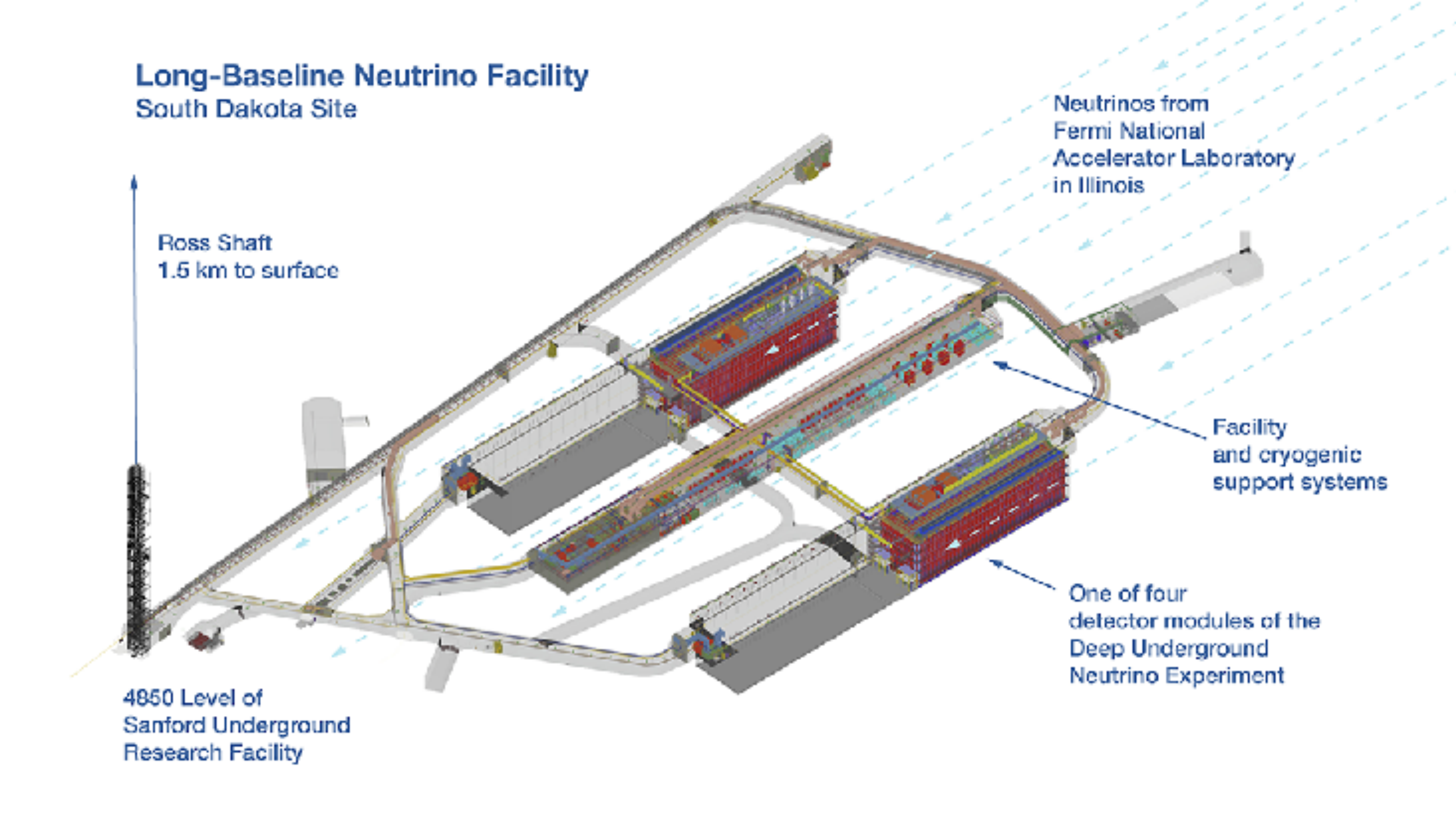
- DUNE will consist of two neutrino detectors placed in the World's most intense neutrino beam, provided by the **Long-Baseline Neutrino Facility (LBNF)**



- One detector will record particle interactions near the source of the beam at Fermilab

- The second, much larger, detector will be installed 1.5 km underground at the **Sanford Underground Research Facility (SURF)** in Lead, South Dakota—1,300 km downstream of the source

The Deep Underground Neutrino Experiment (DUNE) at Fermilab



- The far-site detector at SURF will comprise four cryogenic 18m high by 19m wide by 66m long calorimeter modules, containing a total of 68,000 metric tons of liquid argon at –184 °C → the largest cryogenic instrument ever to be placed deep underground

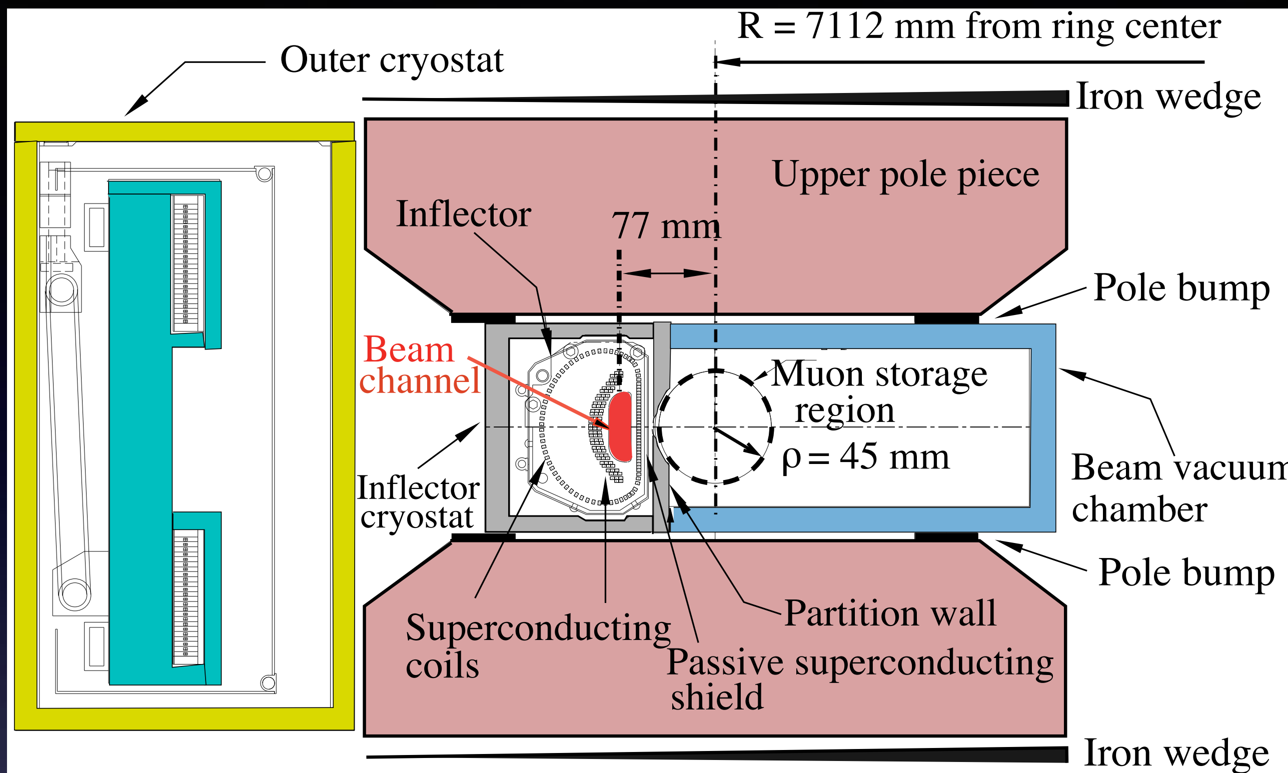
Muons: stress-testing the Standard Model

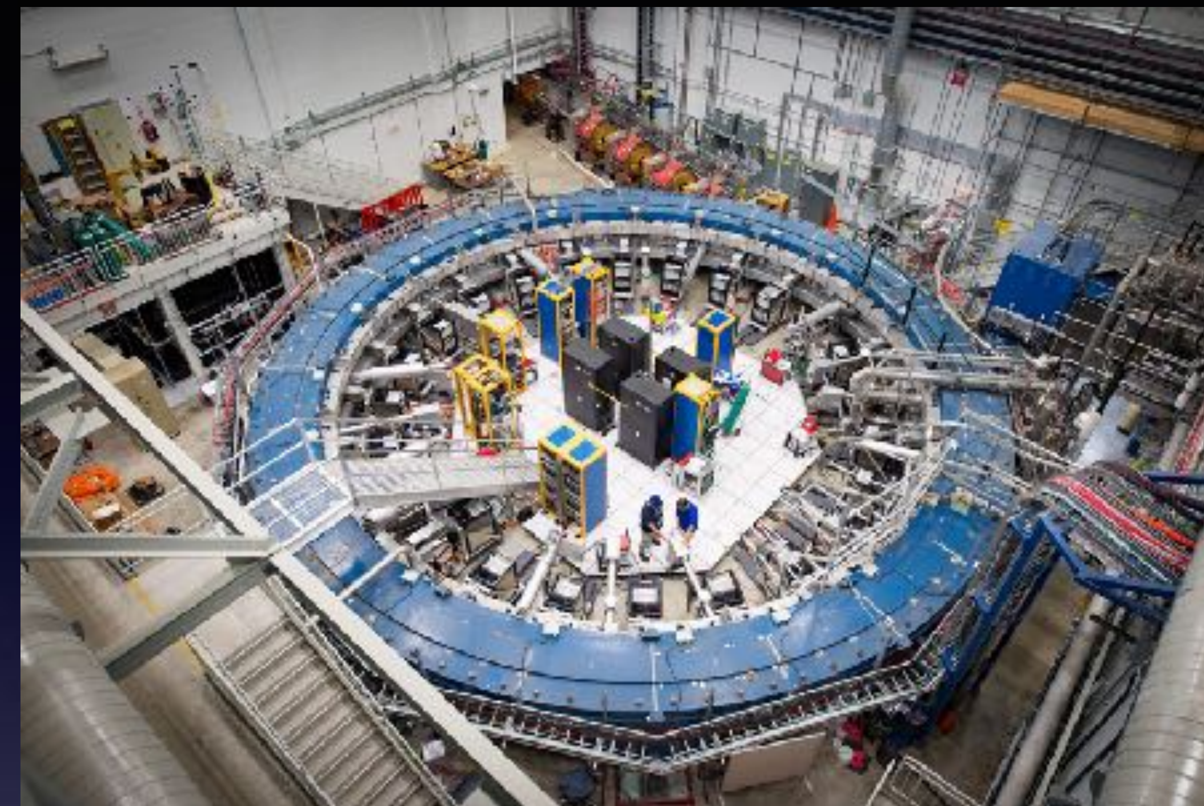
- ✶ The muon, a "heavy electron" (207 times heavier), was discovered by Carl Anderson in cosmic rays in 1936
- ✶ It has many nice features that help its detailed study: elementary, relatively light, easy to produce, with a relatively long mean proper lifetime of 2.2 μs that allows for making muon beams sufficiently stable to investigate various particle phenomena with very high precision
- ✶ It does not interact with the strong force and it is known to decay exclusively into an electron and two neutrinos (one "electronic" and one "muonic") via the weak force
- ✶ Having non-zero electric charge and spin, it behaves like a tiny magnet with a strength proportional to its spin by the "gyromagnetic ratio g", a number very close to 2 (within one part per thousand) that can be measured and calculated very accurately

The g–2 experiment at Fermilab

- ✶ In a magnetic field, the muon wants to align its intrinsic magnet along the field axis, like a compass with the geomagnetic field, but its motion prevents this and makes the magnet axis rotate, or "precess", about the field axis
- ✶ In the quantum world, the vacuum is not just empty space: it is filled with a foam of "virtual" particles, such as massless photons, light electrons and quarks, heavy W, Z and Higgs bosons, or even so massive "exotic" particles that are difficult to create directly in colliders like the LHC
- ✶ While a muon is moving in a magnetic field, it interacts with virtual particles in the vacuum, altering the precession frequency by the amount g–2
- ✶ g–2 has been measured and calculated using the Standard Model with about the same accuracy of 400 parts per billion, and the two results disagree at a level of 0.03% likelihood to be consistent, hinting at the existence of yet unobserved particles in the vacuum

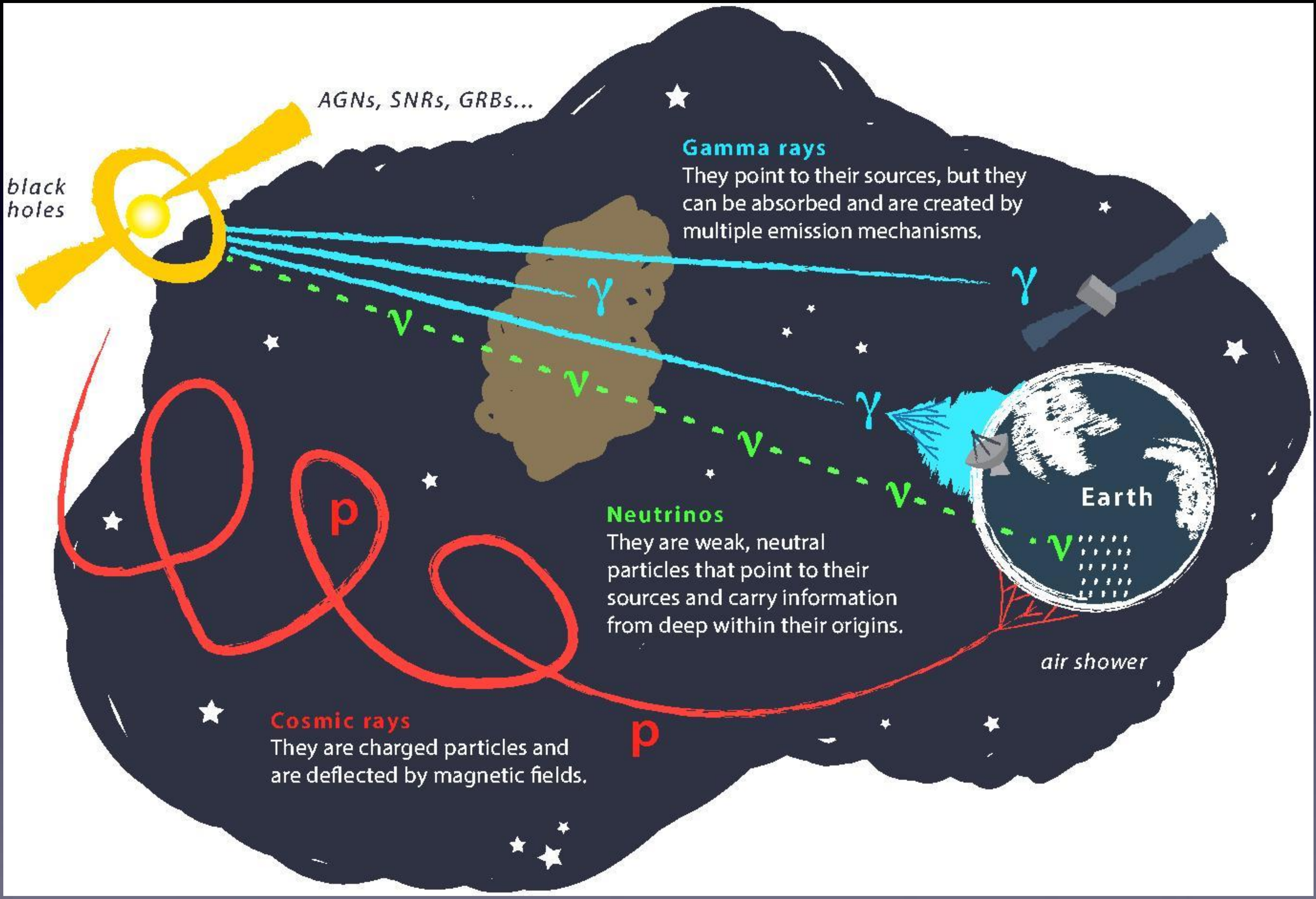
The g–2 experiment at Fermilab





- ✶ A **longitudinally polarised** muon beam is injected into a magnetic storage ring with the field perpendicular to the muon beam
- ✶ The energy of positrons produced by muon decays in the ring is correlated with the precession angle of the muon spin and is measured in calorimeters regularly placed along the ring
- ✶ The precession frequency is measured from the undulation pattern of the positron energy distribution and, together with the field strength, yields g–2
- ✶ The experiment aims to measure g–2 with a precision of **140 parts per billion**, which will definitely resolve the tension with the Standard Model

Astro-particles: multi-messenger astronomy



The IceCube experiment

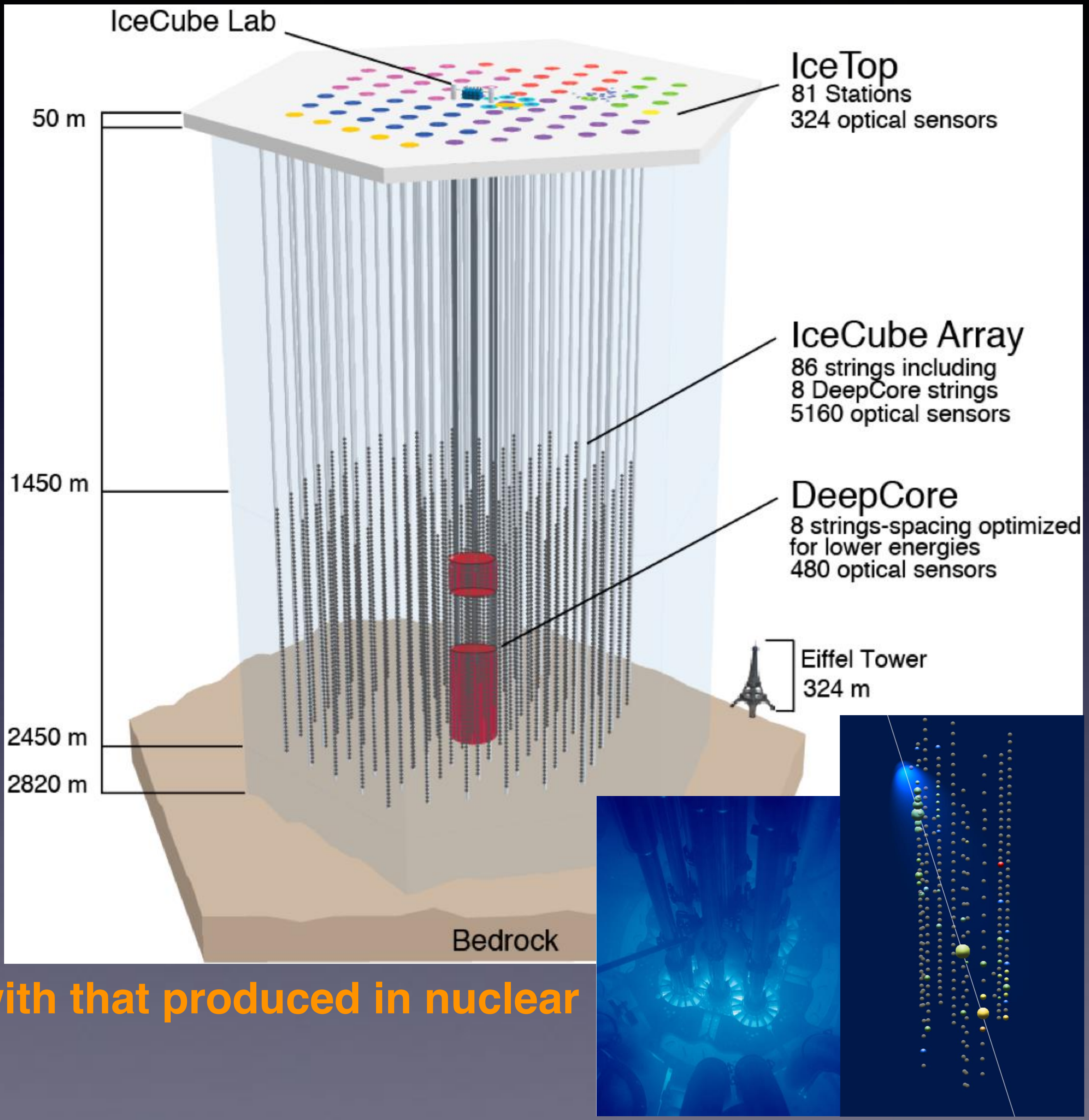
- ★ **Installed at the geographical South Pole in Antarctica**
- ★ **Reachable from mid November to mid February, but continuously operating**
- ★ **Uses large volume of pure ice for neutrino detection and the Earth as a shield against other cosmic particles**
- ★ **Aims to study neutrino properties at very high energies (thousands to millions of times higher than the LHC energy) and the nature of the sources of such energetic neutrinos**

The IceCube experiment

- ★ A high-energy neutrino interaction creates energetic charged particles

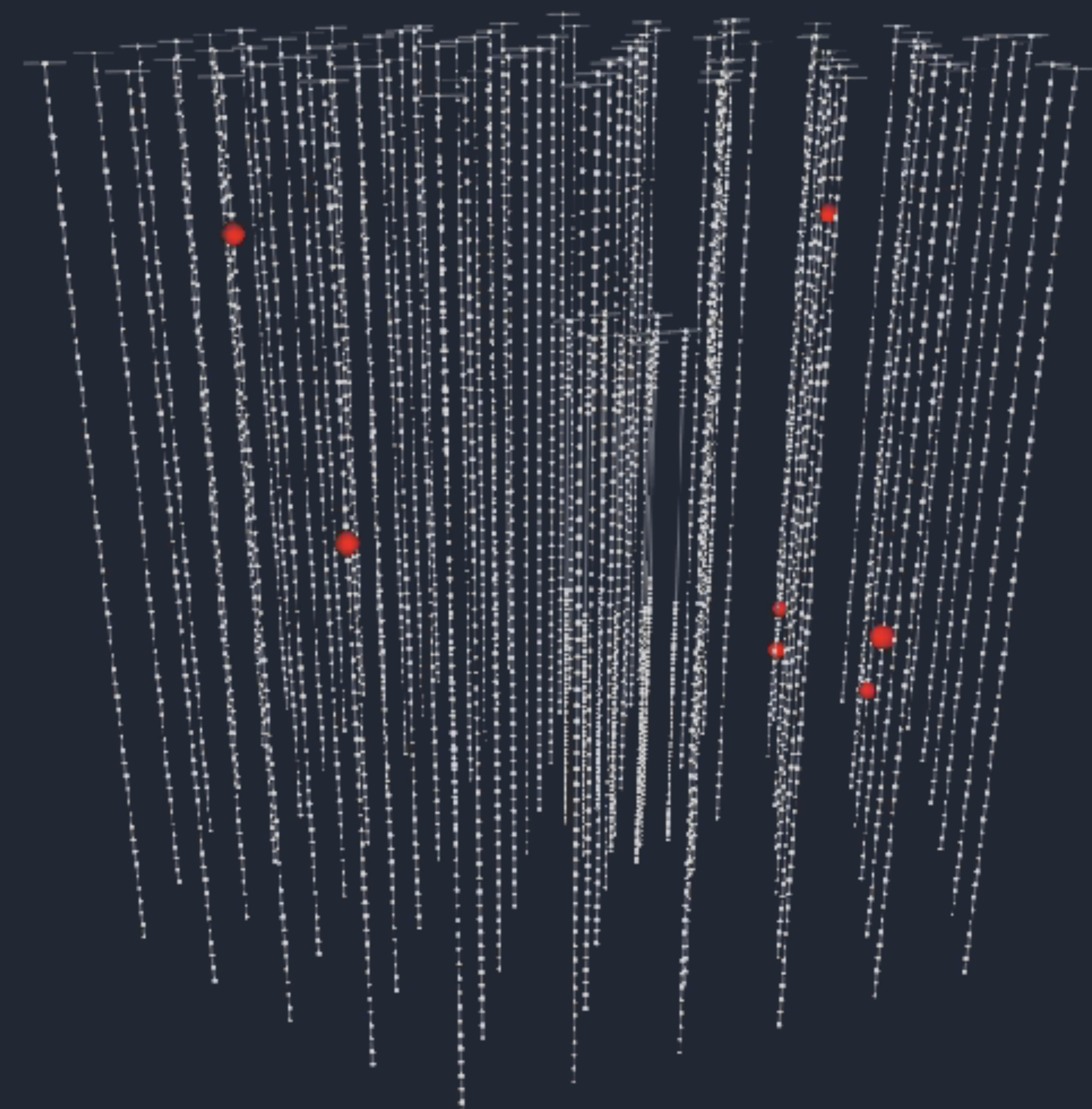
- ★ When these travel faster than the light travels in the ice, they emit Cherenkov radiation

- ★ Optically transparent ice allows this light to reach some of the 5160 photo-sensitive sensors installed in the ice



- ★ This UV/blue light is the same with that produced in nuclear reactors

The IceCube experiment



IC170922A
Alert sent
Sep 22, 2017
via *Realtime* stream

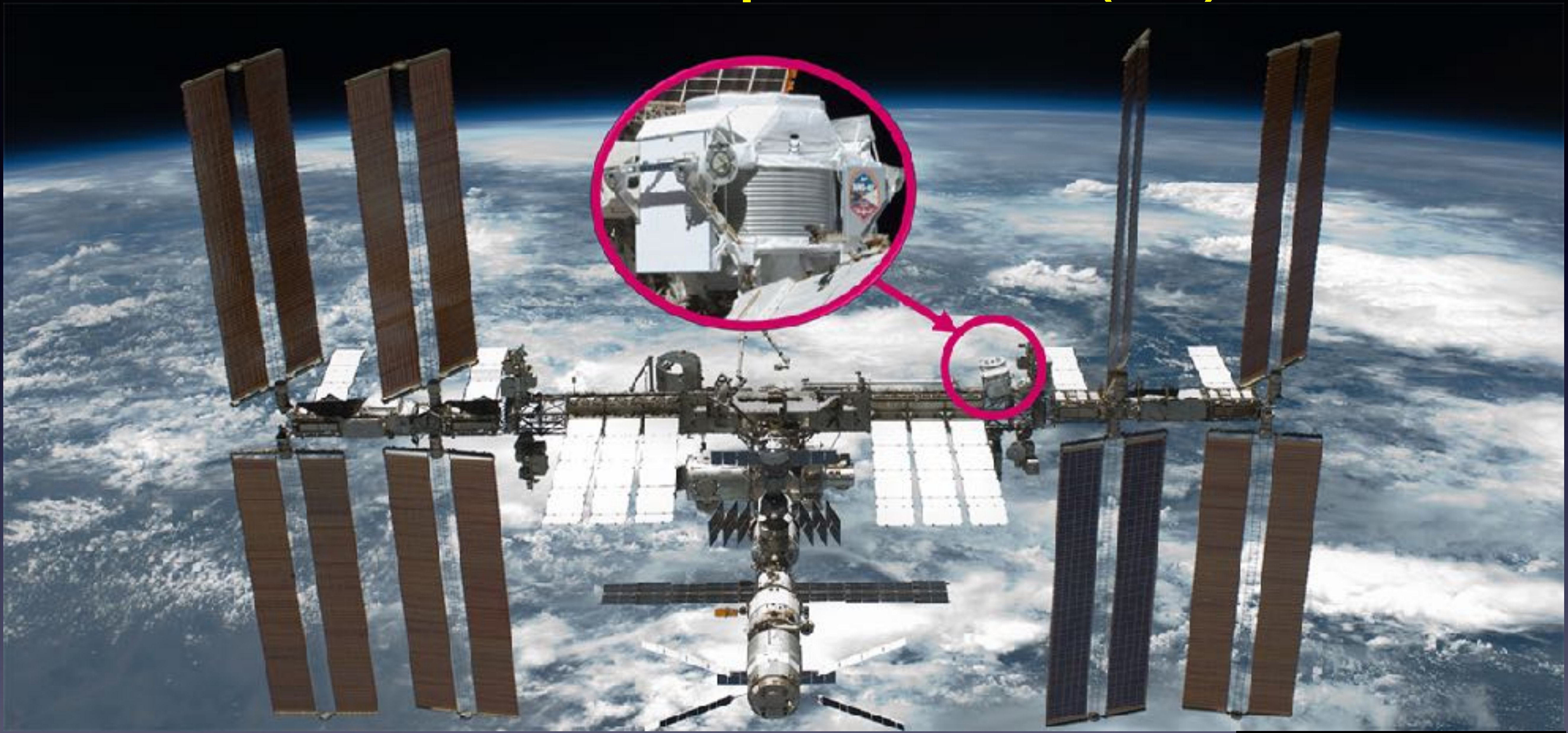
E ~ 290 TeV

Signal probability:
56.6%

Coincident observations by Fermi-LAT and MAGIC

Science 361 (2018) no.6398, eaat1378

The Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)



- ★ The **first precision particle physics detector in space**
- ★ Installed on ISS in the last mission of the space shuttle Endeavour in 2012
- ★ It searches for antimatter and for the nature of dark matter

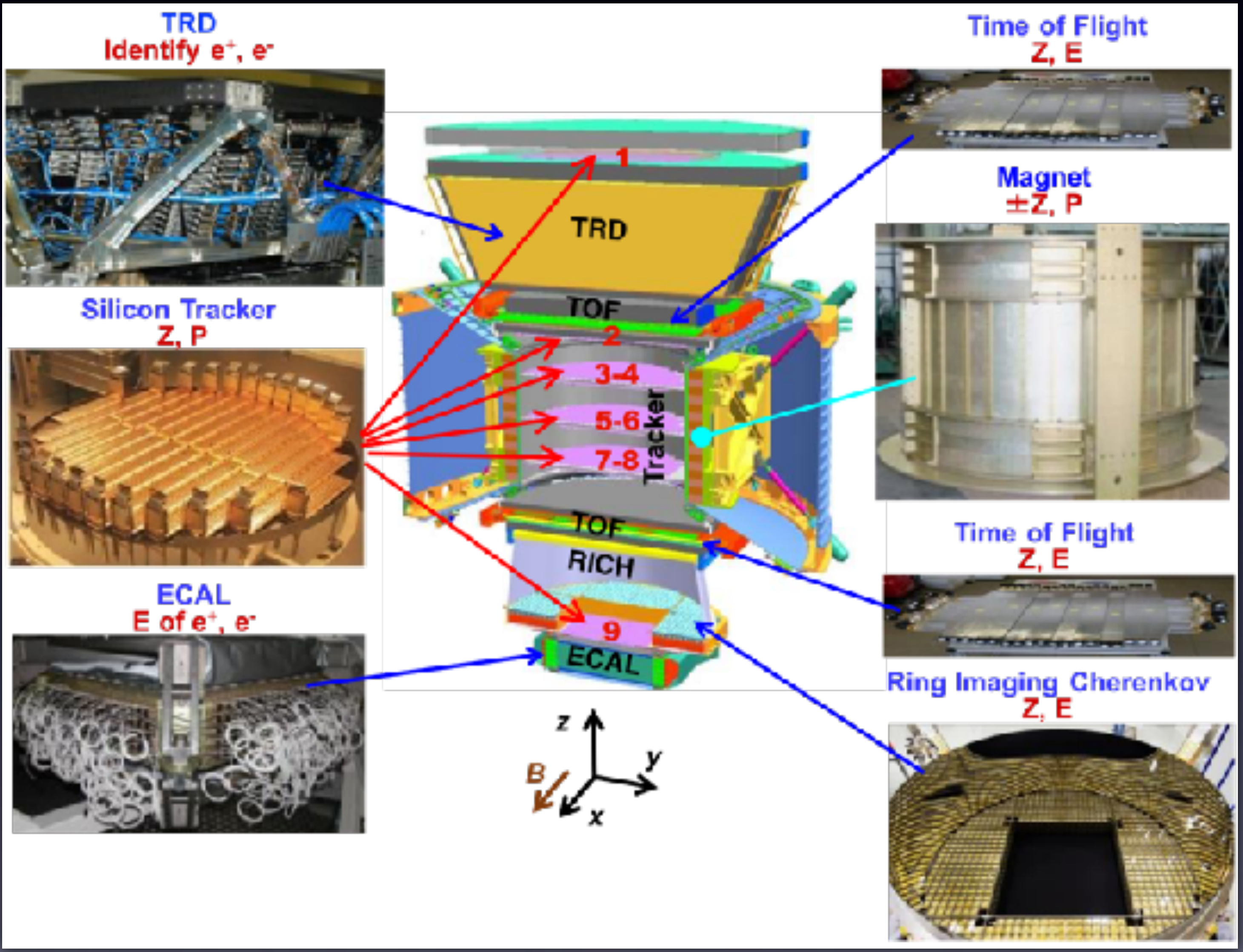
The Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)

★ AMS consists of a magnet surrounded by an array of detectors to identify the passing particles and nuclei and measure their momentum and charge:

★ The Transition Radiation Detector (**TRD**) identifies electrons and positrons and discriminates nuclei

★ The **silicon tracker** is the central instrument for high-precision measurements of charge and momentum

★ The Time Of Flight (**TOF**) counters initiate event recording (trigger)



★ The Ring Image Cherenkov (**RICH**) counter measures the charge and velocity of the passing particles and the Electromagnetic Calorimeter (**ECAL**) measures the momentum of very energetic electrons and positrons

Summary

- The Standard Model (Theory) of Particle Physics explains the Universe we see
- This is one of the greatest achievements in the history of human culture
- Yet, the Standard Model does not explain the Universe we do not see (but we do observe its traces)
- Big experiments at the frontier of human technology look for answers to big questions about the Universe

The long quest for knowledge of the Cosmos continues more exciting than ever!