A brief introduction to “Fundamental Physics”

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African School of Physics 2018, Windhoek, Namibia

Goals of this talk

- Present an introduction to fundamental physics designed for non-specialists
  - Most of you are specialists, so you'll know much of what I say, but the idea is to provide material that could be useful when presenting this to your students
    - Please feel free to reuse any material
- Fundamental Physics is an extremely broad topic
  - I decided to interpret is as "What is fundamental?"
  - Please excuse me for not including your favourite topic in fundamental physics
- I like questions and discussion
  - Please feel free to interrupt me

Two (ancient) key questions

- What are the fundamental components ?
- How do they interact with each other ?

?

"By convention there is color,
By convention sweetness,
By convention bitterness,
But in reality there are atoms
and space."

-Democritus (c. 400 BCE)

Learning how to play chess

First, learn the pieces

Fundamental Components

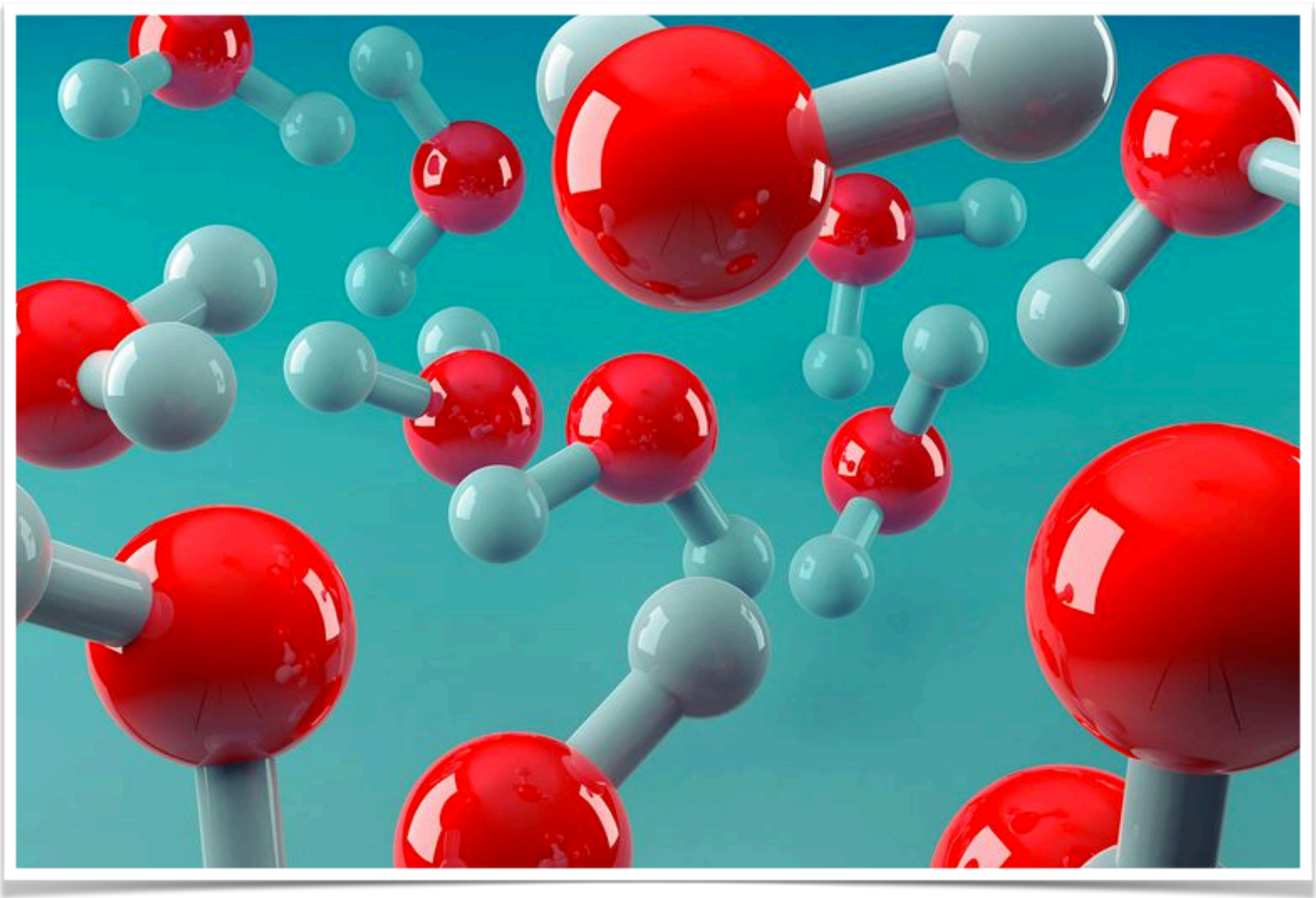
- Greeks: fire, air, earth and water
- China: earth, wood, metal, fire, water
- India: space, air, fire, water, earth

Getting started

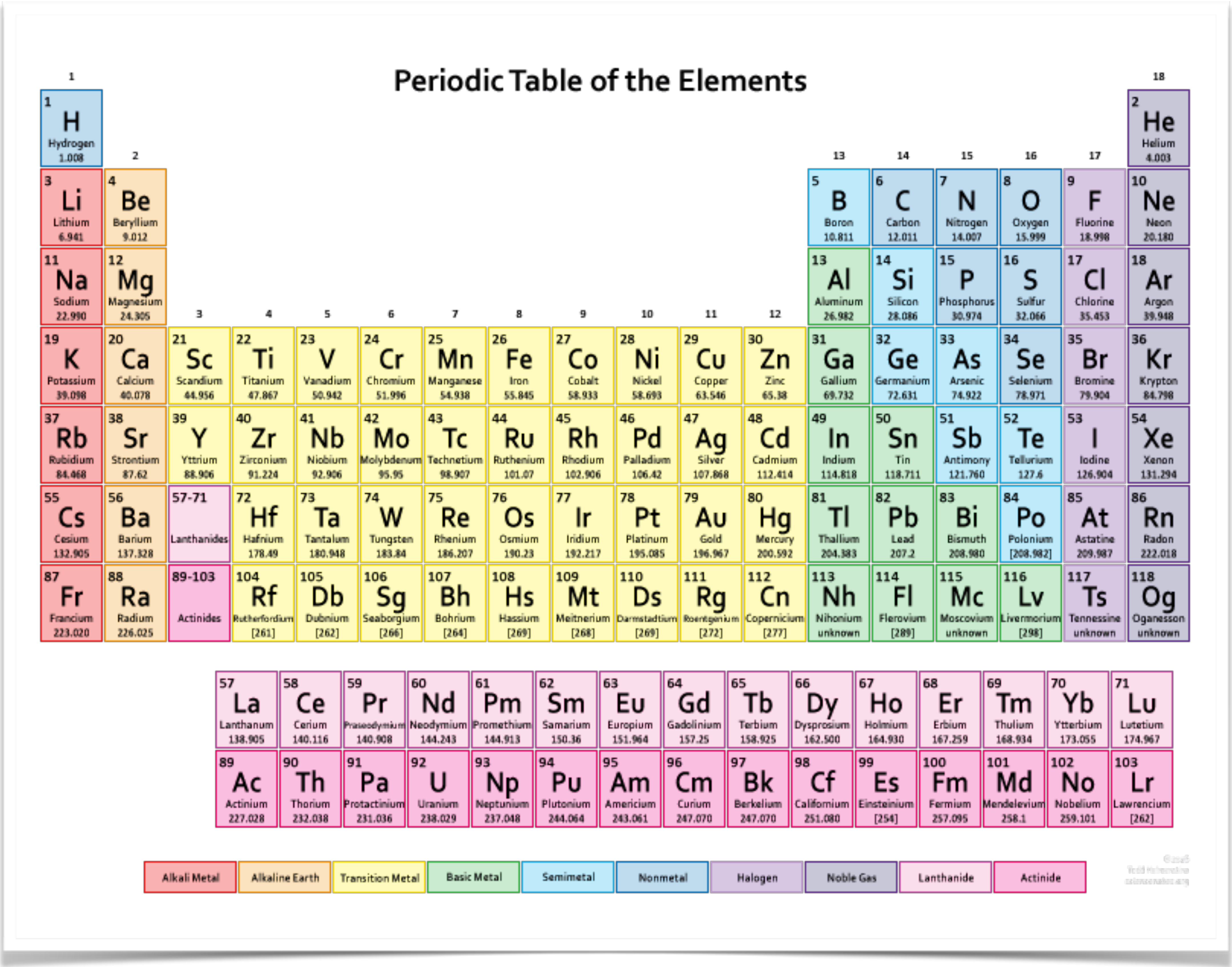
- Before delving into the world of tiny particles, let's start with something a bit more familiar
- Let's ask … what are you made of ?

(ASP2018)

First answer: Molecules



Second Answer: Atoms



https://sciencenotes.org/printable-periodic-table/

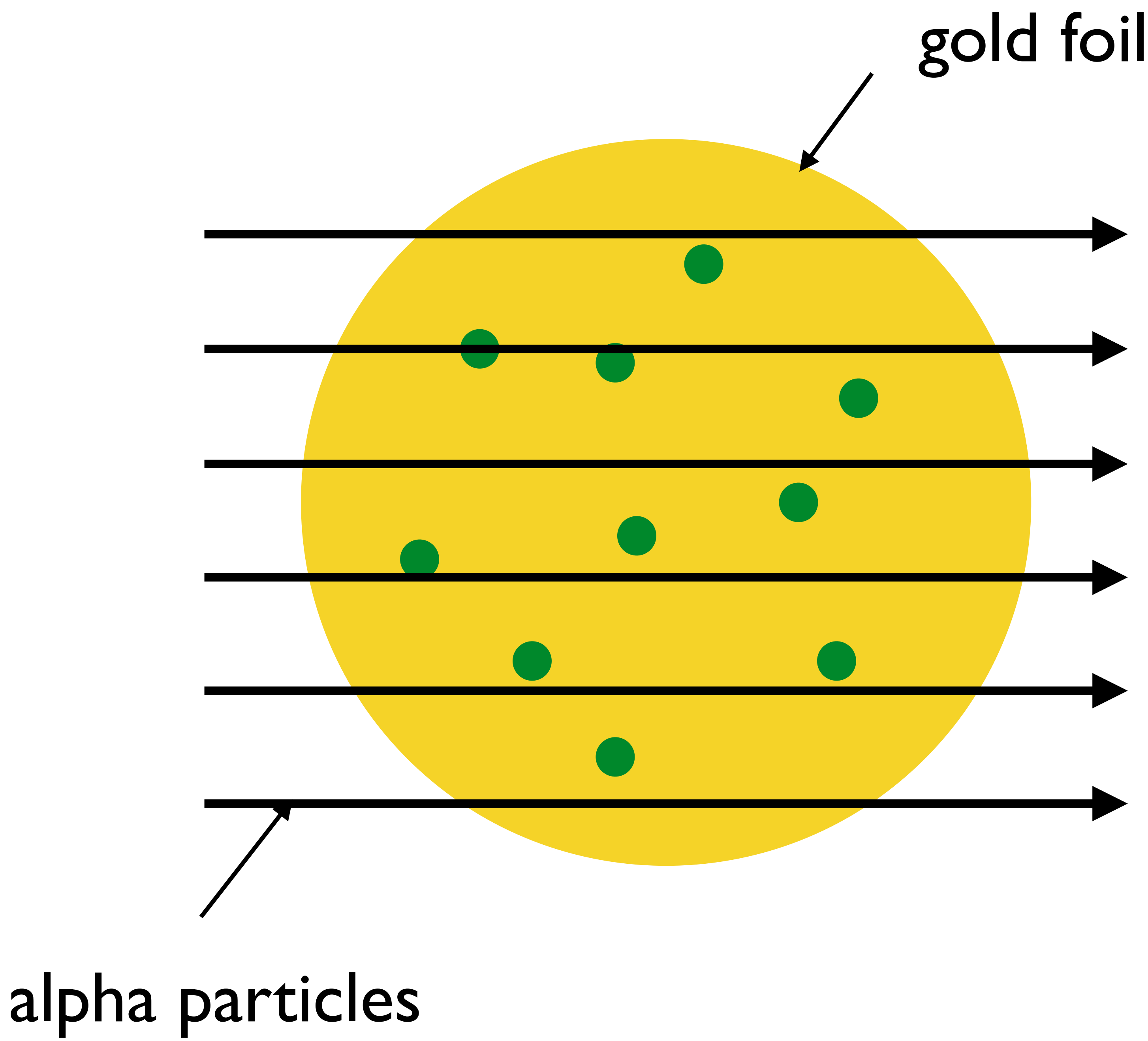
The Atom

- ~1900: atom more fundamental than earth, space, fire, water …

- But is the atom truly fundamental ?
  - experiment !

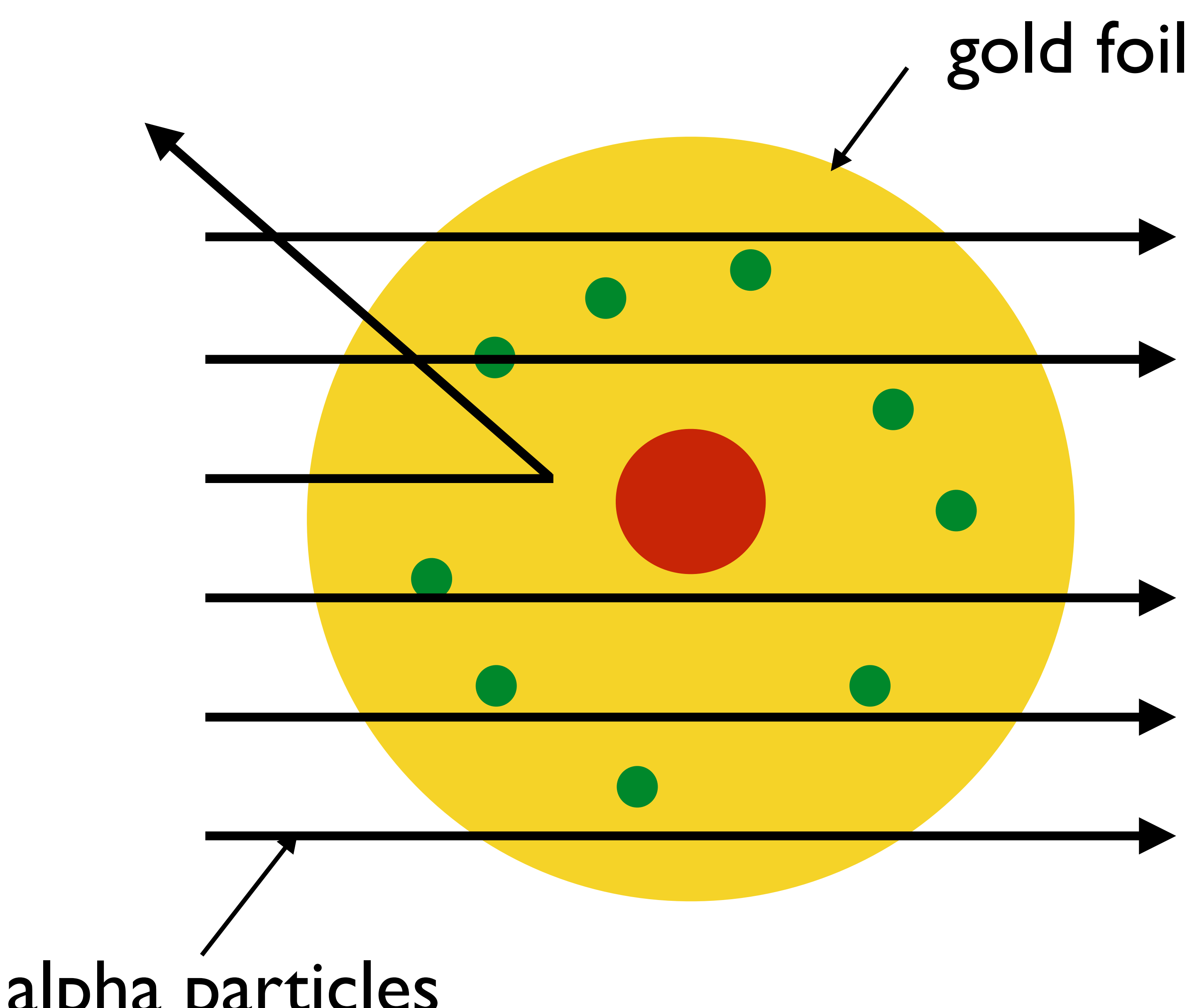
Geiger-Marsden Experiment (1909)

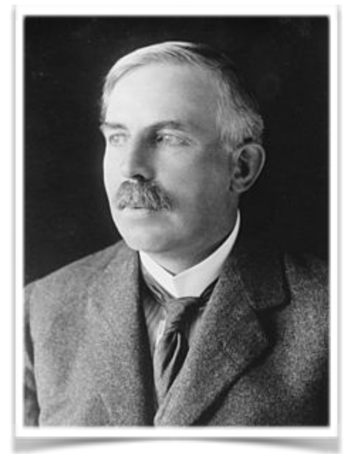
- Theory: atom was filled with diffuse charge
- Expectation: Alpha particles would pass through the foil



Geiger-Marsden Experiment (1909)

- Some particles did pass through the film
- But others were deflected at large angles
  - as if they'd hit something hard and dense
  - like a nucleus …

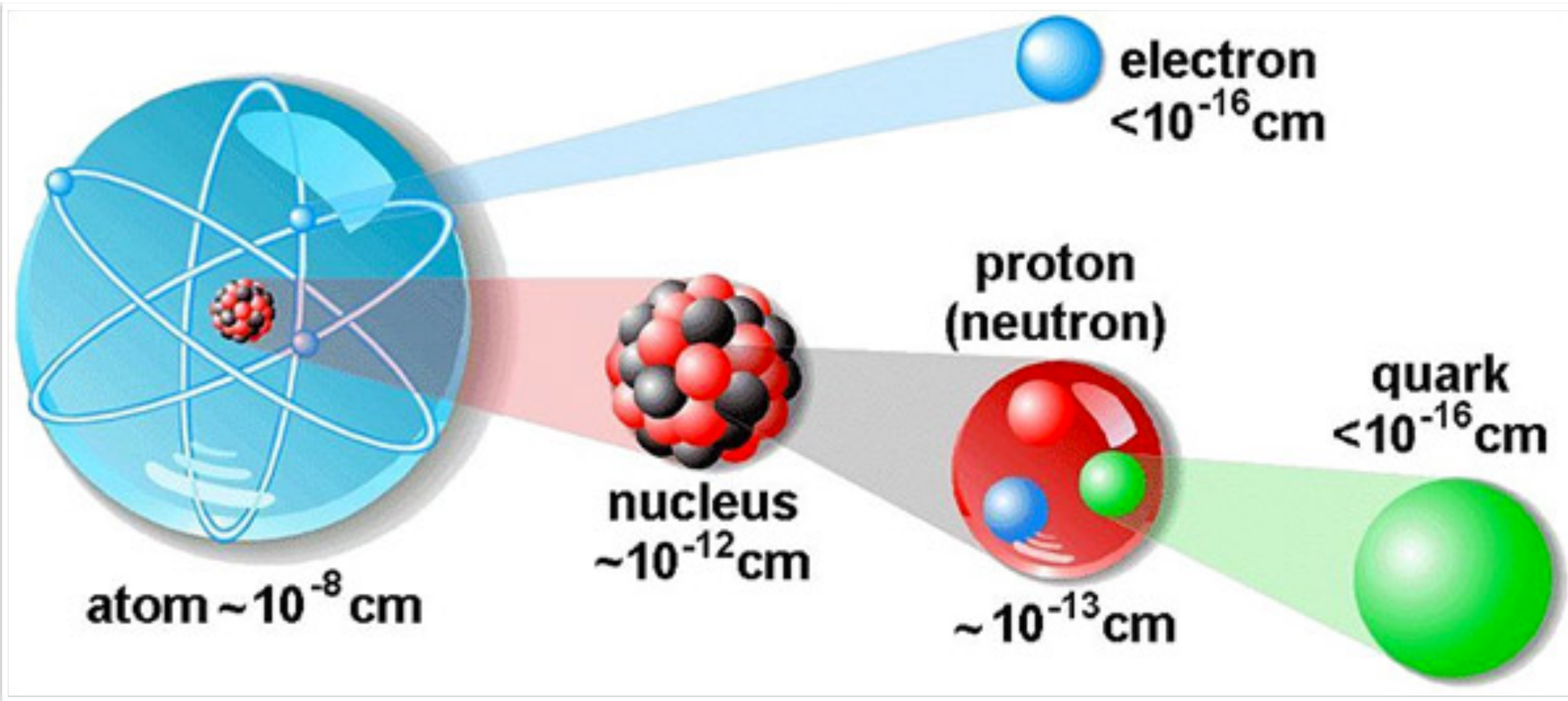




"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Ernest Rutherford

Current answer: quarks!



Reminder: Tiny Numbers

- 10^{-22} m is quick to write, but it’s a deceptively tiny number
  - 0.0000000000000000000001 m

22 zeros

Tiny Numbers

atom

10^{-18} m

1 m

10^{18} km

1 km

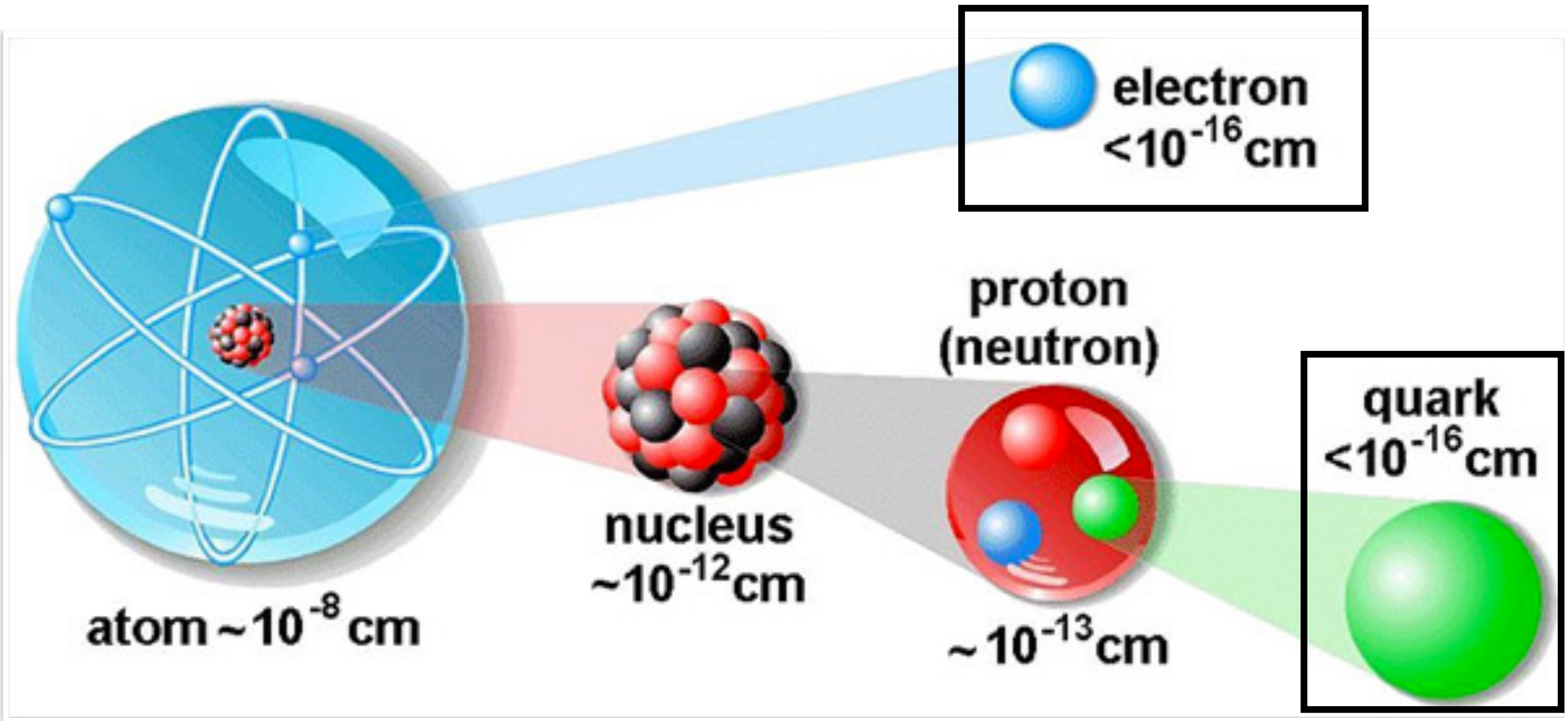
The Standard Model

- Our current fundamental* theory
- **Matter**: the fundamental constituents of the universe
  - the elementary particles
- **Force**: the fundamental forces of natures
  - interactions between elementary particles

*until proven otherwise

Matter

- Two types of matter
  - quarks
  - leptons, e.g. electron, also neutrinos*



*neutrinos are very interesting (and weird) particles, but we don't have time to discuss them in detail during this course

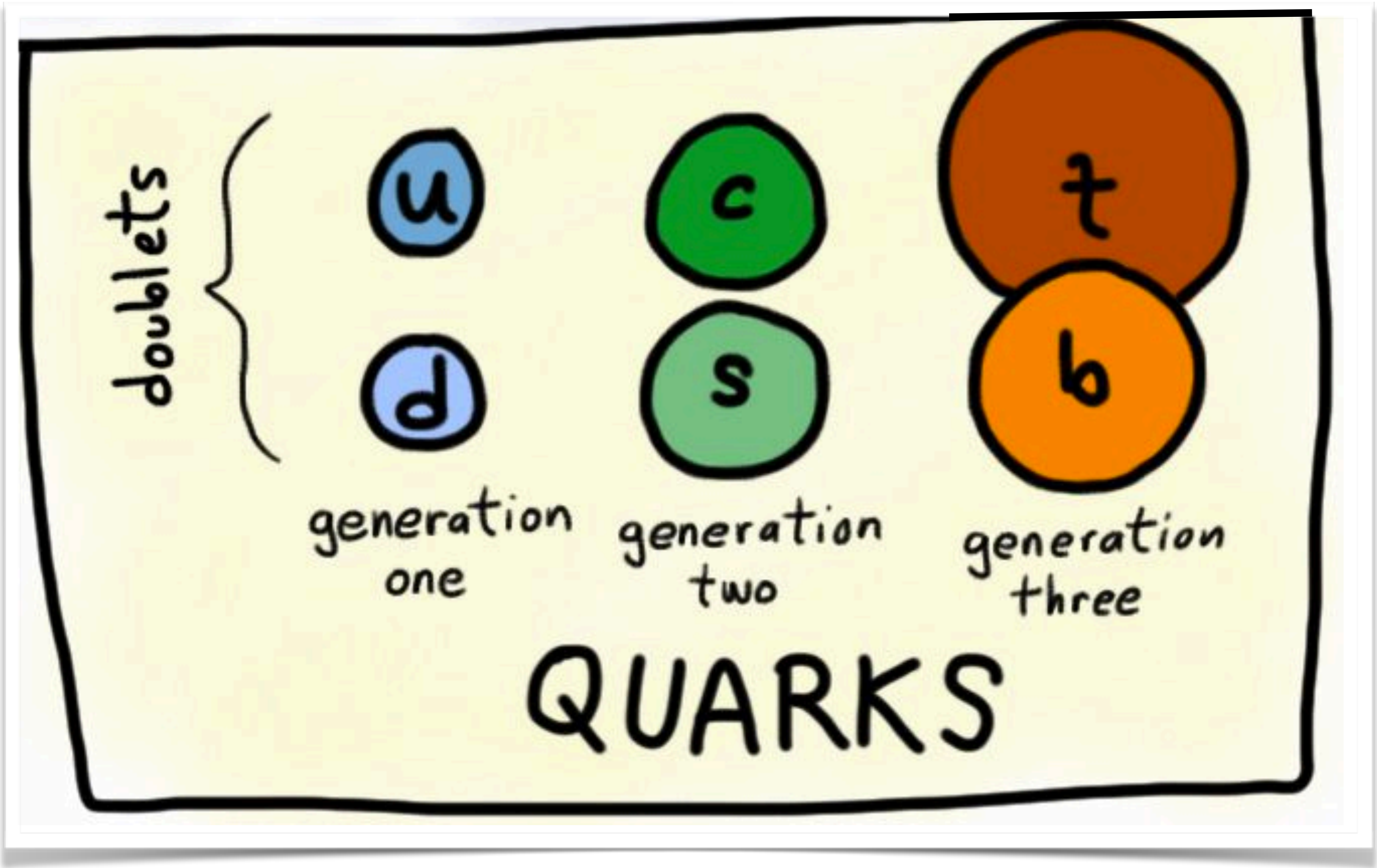
Ordinary Matter

Image courtesy of Y. Beletsky

Something weird … clones !

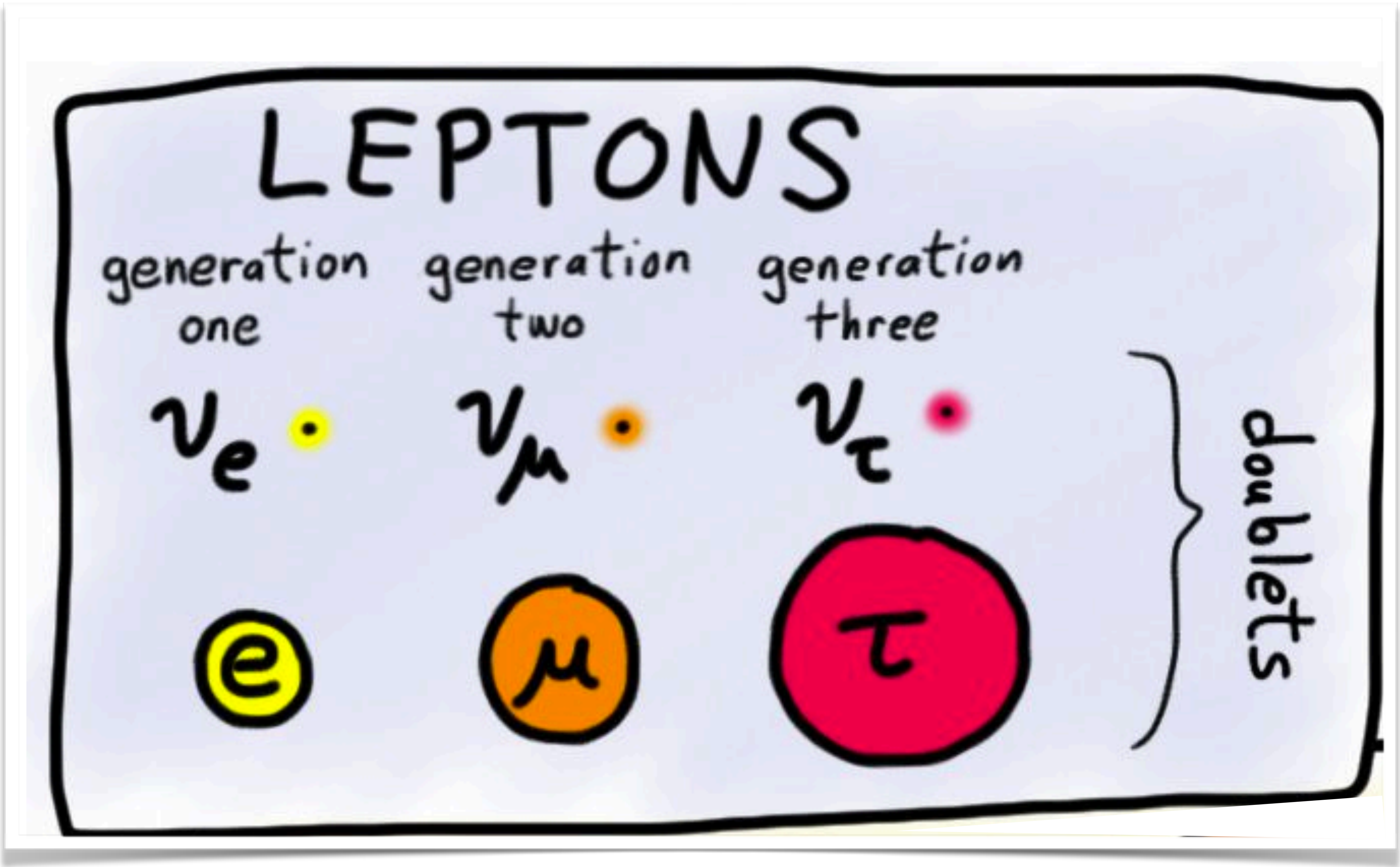
Credit: Courtesy Daisuke Takakura

Quark Families



Credit: https://phys.org/news/2012-10-platypus-particle.html

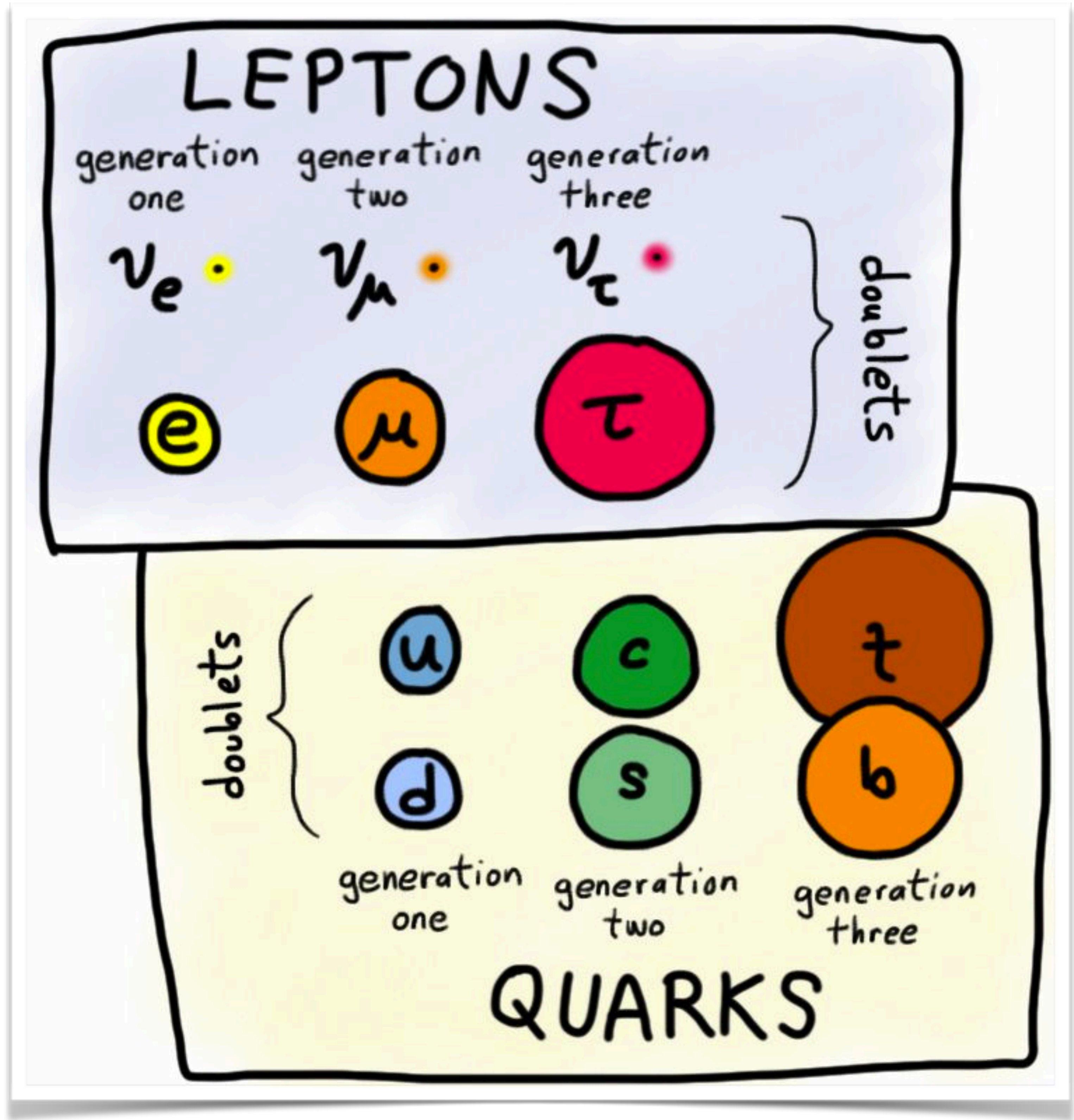
Lepton families



Credit: https://phys.org/news/2012-10-platypus-particle.html

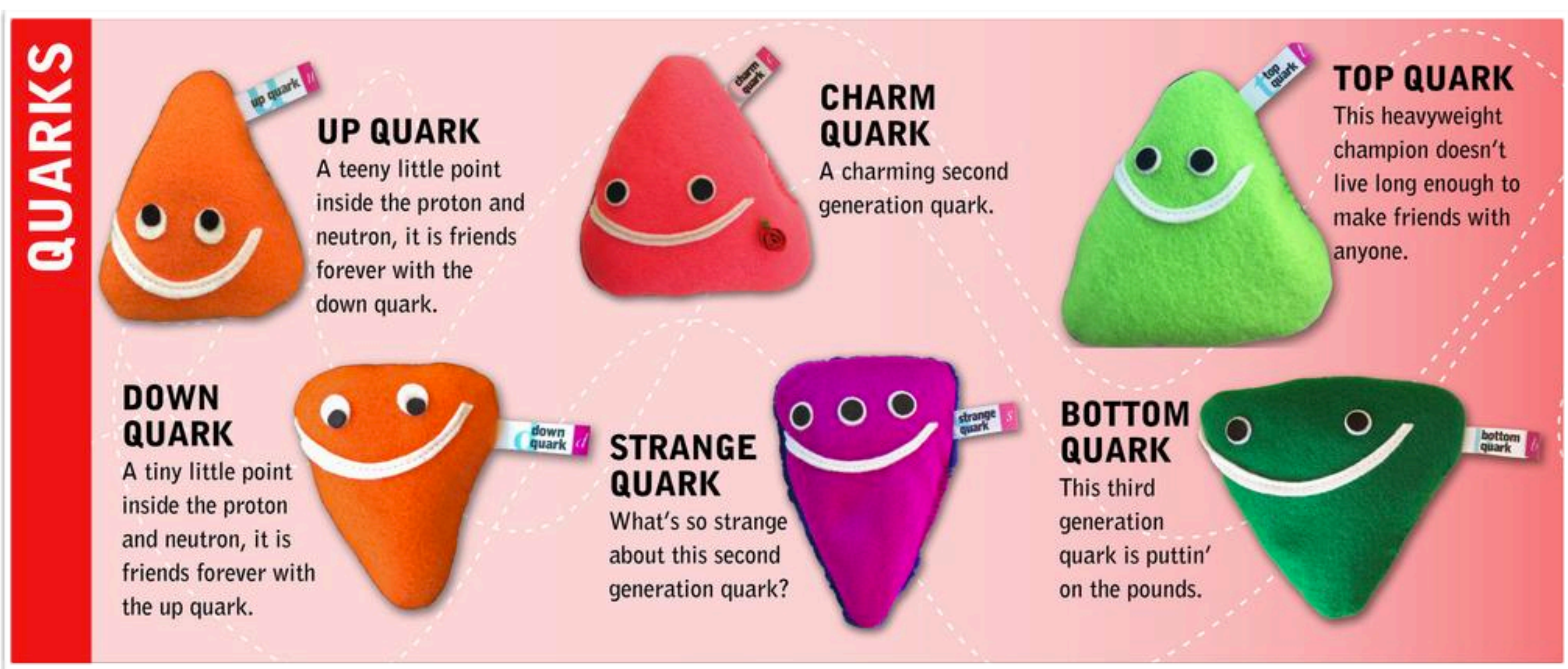
Why are there six quarks and leptons ?

- Deep question
- We know there are three copies of quark and leptons, but we do not know why
- Only need up and down quarks and electrons to make ordinary matter
  - But experiment tells us that they exist



Why do they have such silly names?

- Initially: **up** and **down**
- **Strange**ly long kaon lifetime
- **Charm** quark was named at random
- Finally: **truth** and **beauty** but most often top and bottom



Physicists have a sense of humour?

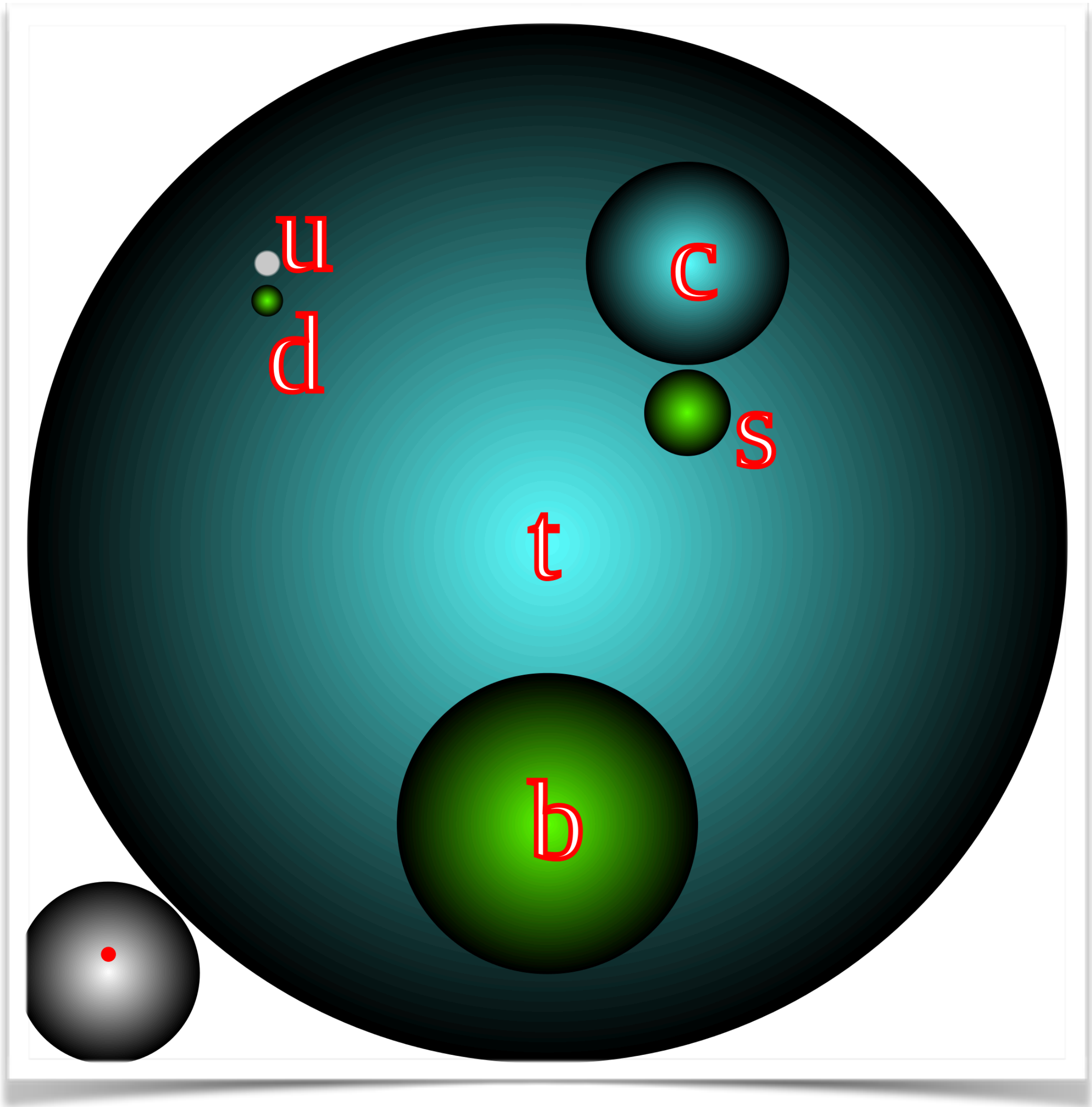
Credit: Particle Zoo

How big is a quark?

- We don't know !
- Our theories tell us that they are point-like
  - i.e. that they have no size
- But that doesn't stop us trying to 'measure' their size*
  - Currently, we know they are smaller than 10^{-18} m

Quarks Summary

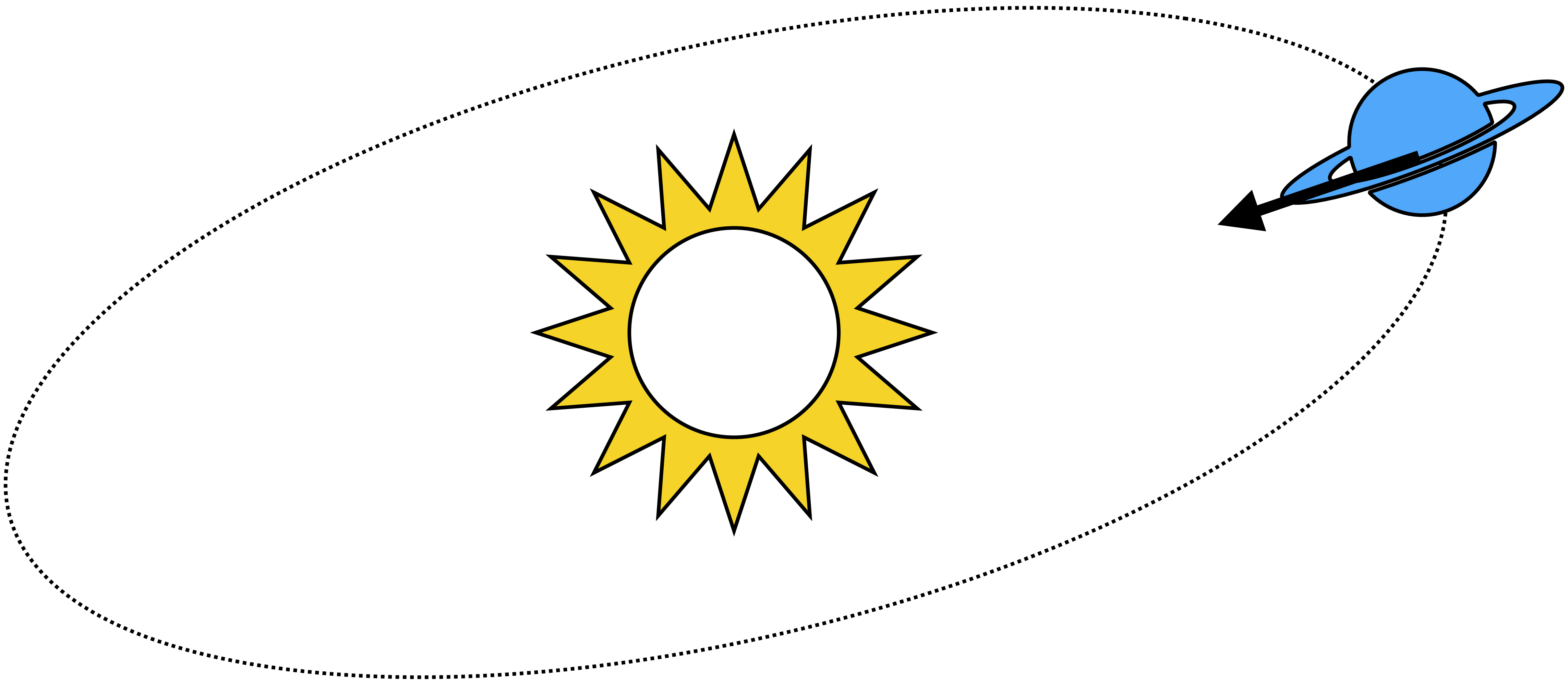
The **top** quark is 60000 times heavier than the **up** quark
Why? Again, we don't know yet



Credit: Incnis Mrsi - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22760588

Now we know the pieces … but we still need to know the rules

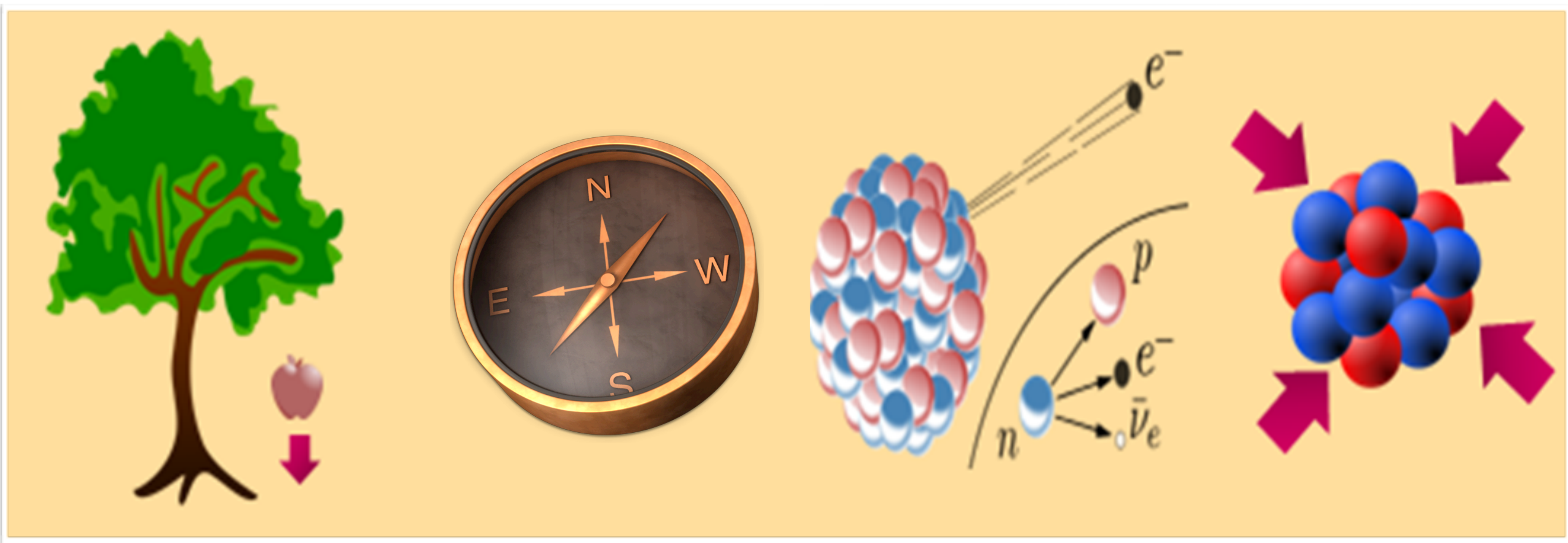
Particles interact via forces



Gravitational force fully defines the orbits of planets around the sun

Four Fundamental Forces

Gravitation | Electromagnetism | Weak | Strong

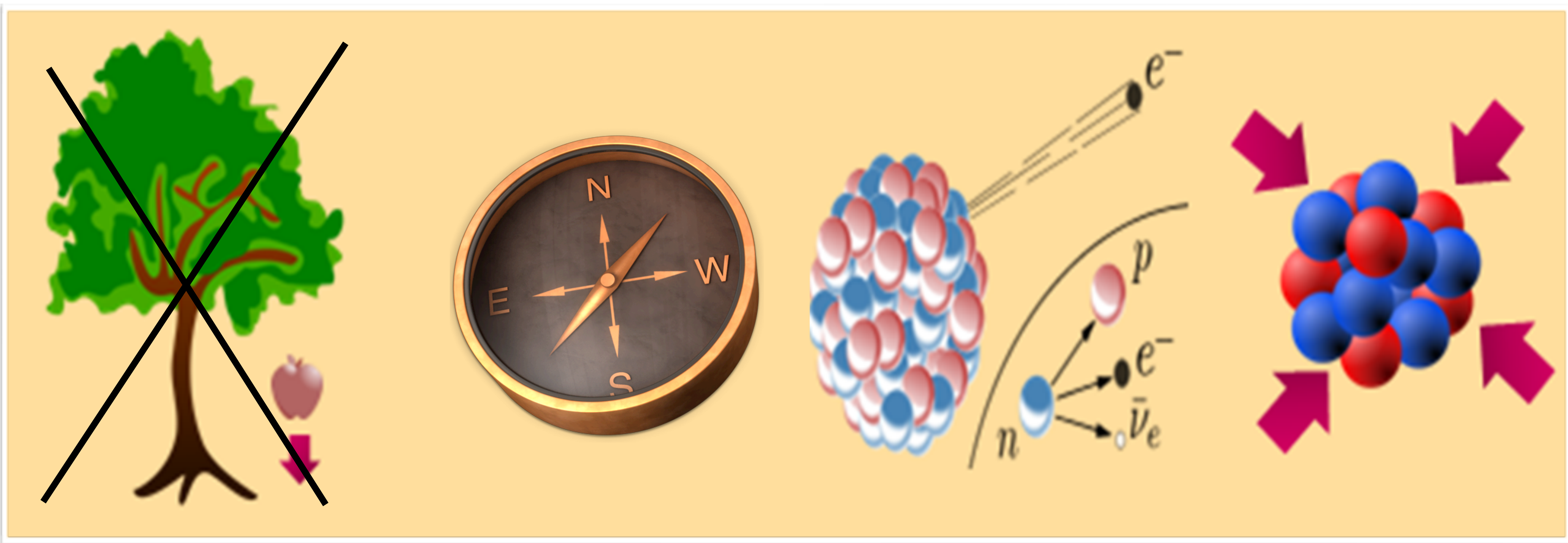


graviton | photon | W/Z boson | gluon

Credit: https://commons.wikimedia.org/wiki/File:FOUR_FUNDAMENTAL_FORCES.png

Four Fundamental Forces

Gravitation **Electromagnetism** **Weak** **Strong**

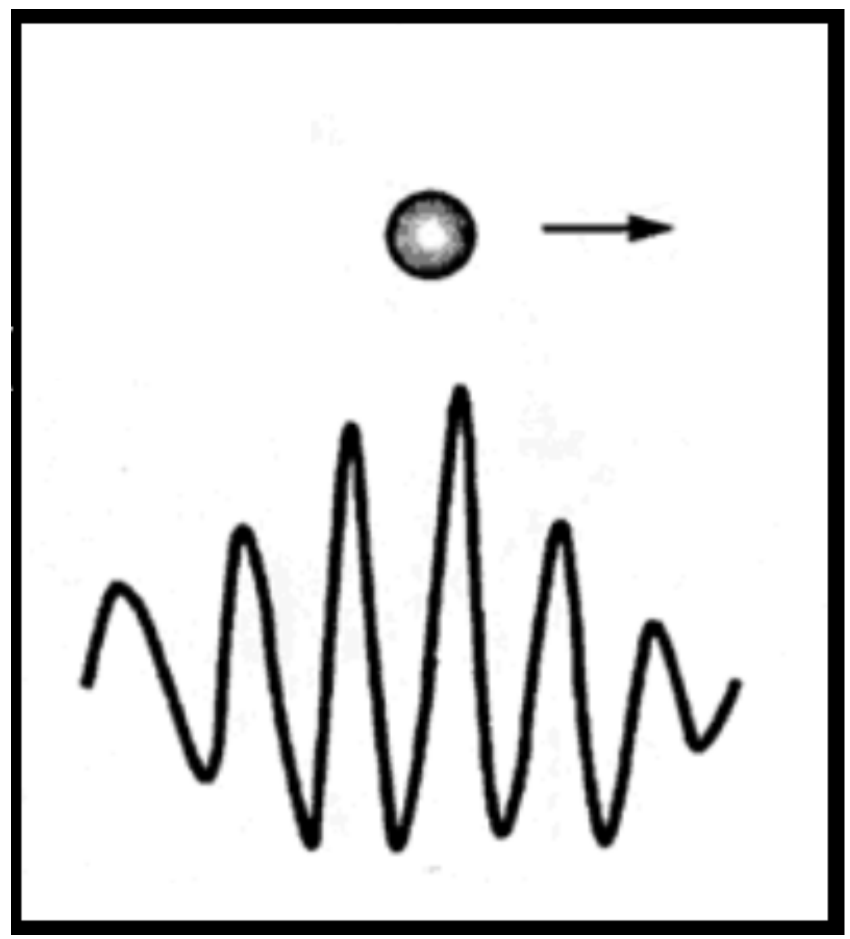


graviton **photon** **W/Z boson** **gluon**

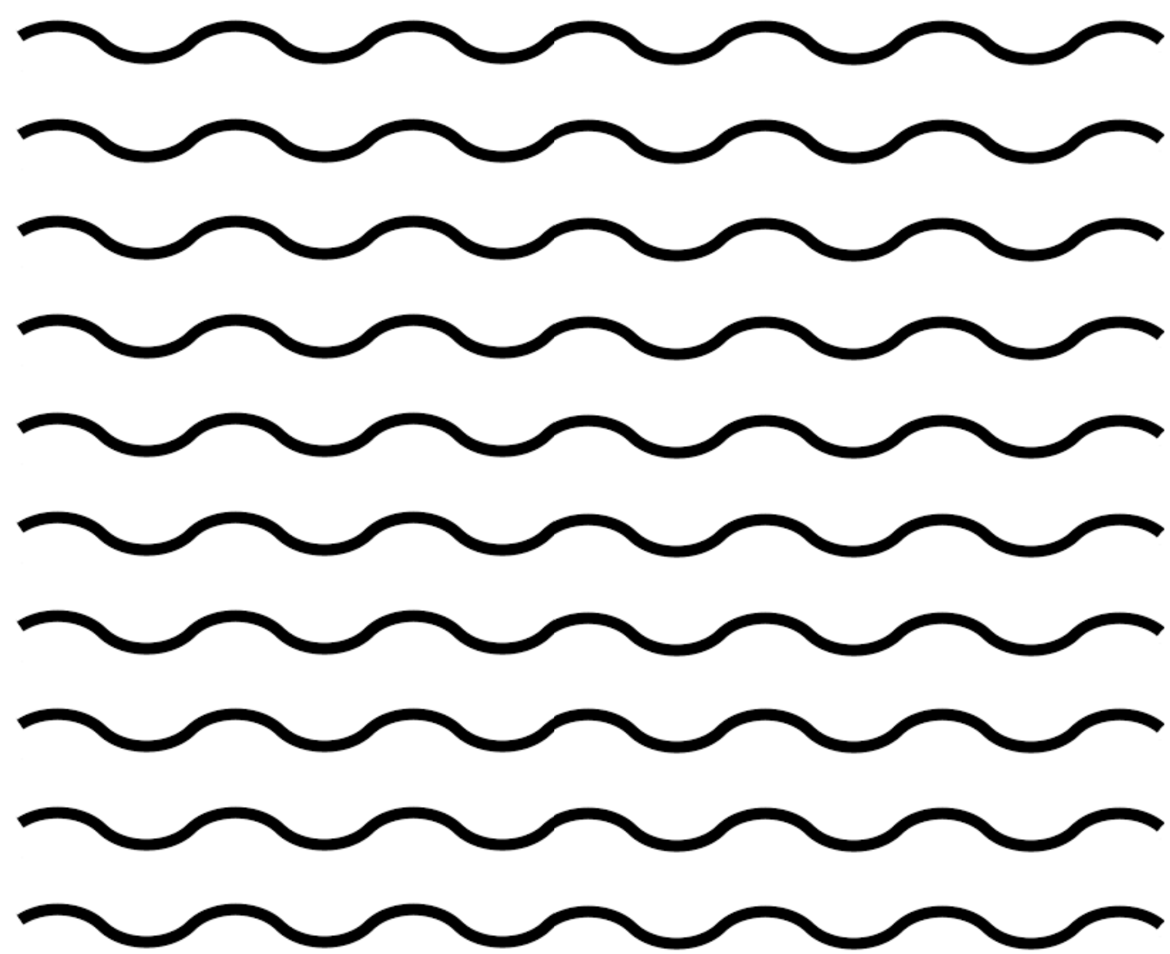
Credit: https://commons.wikimedia.org/wiki/File:FOUR_FUNDAMENTAL_FORCES.png

Wave-particle duality

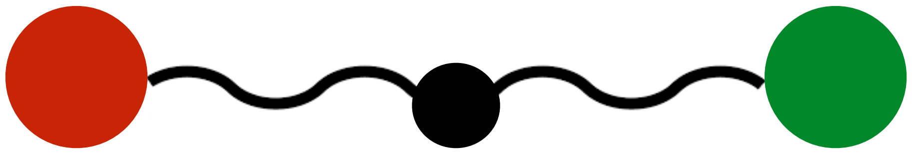
- Strange feature of quantum mechanics
- Simultaneously particle and a wave/field



Field

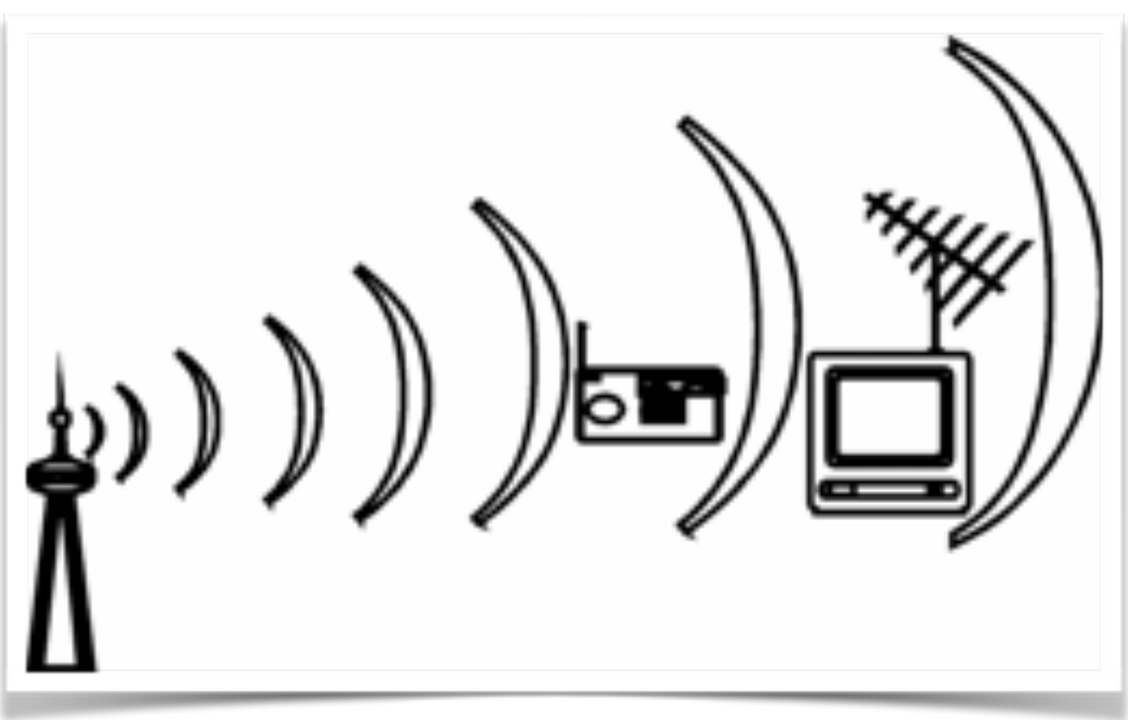


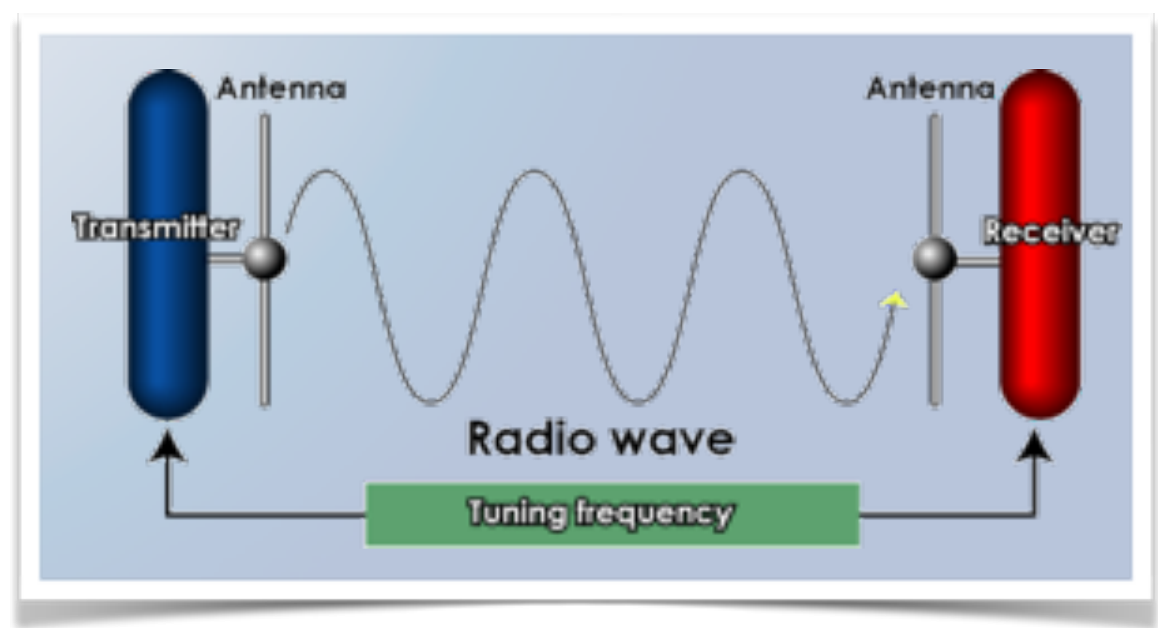
Particle



The Electromagnetic Force

- Electromagnetic force acts on any particle with charge
- Transmitted by the photon
- Because the photon is massless, the electromagnetic force acts over an infinite range
- We use the electromagnetic force extensively



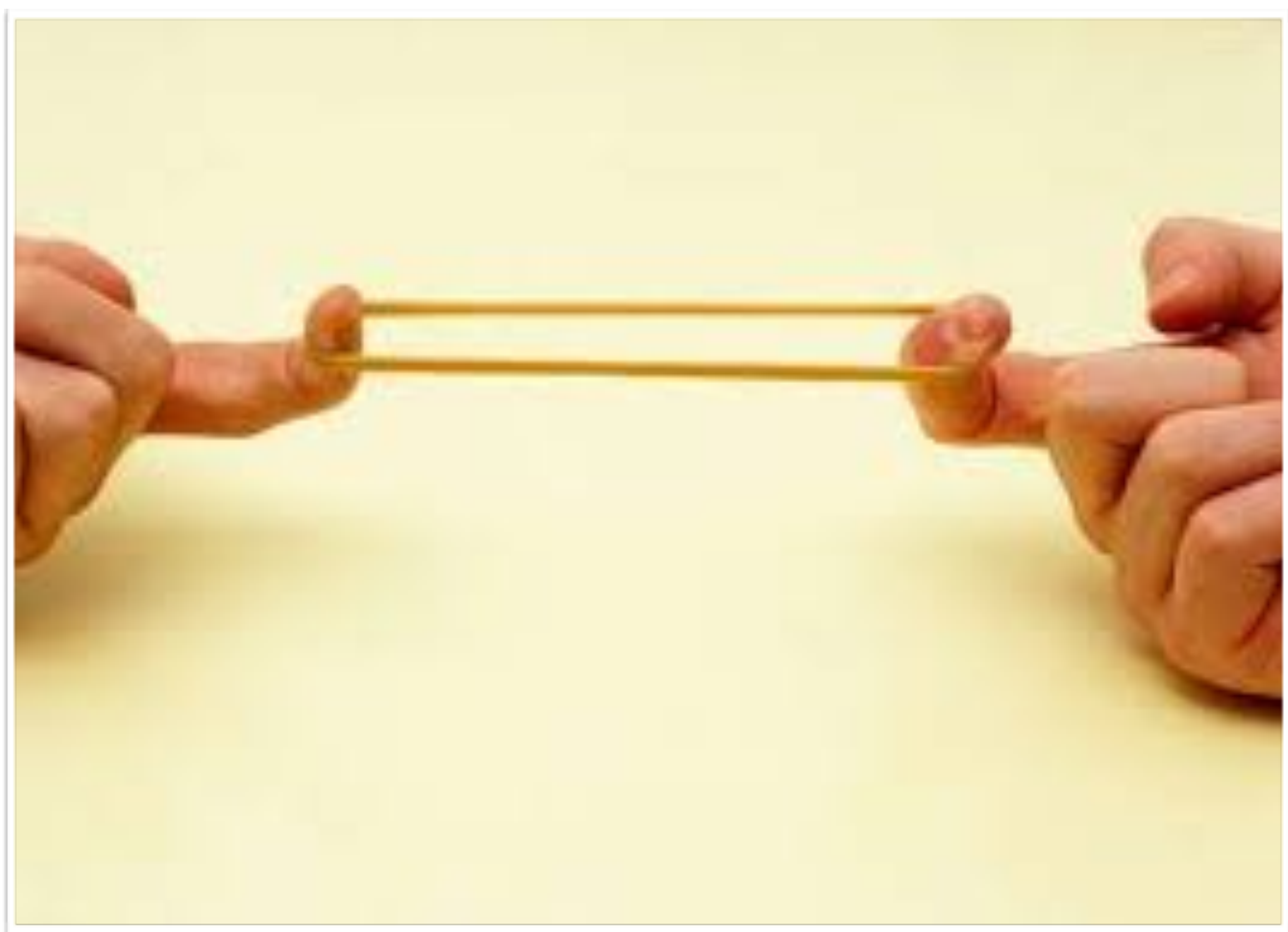


The Strong Force

- Strong force acts on all particles that have colour
- Strong force binds protons and neutrons together in the nucleus
- Carrier of the strong force is the gluon
- Fun fact: strong force is actually the origin of most mass of every day objects, not the Higgs boson

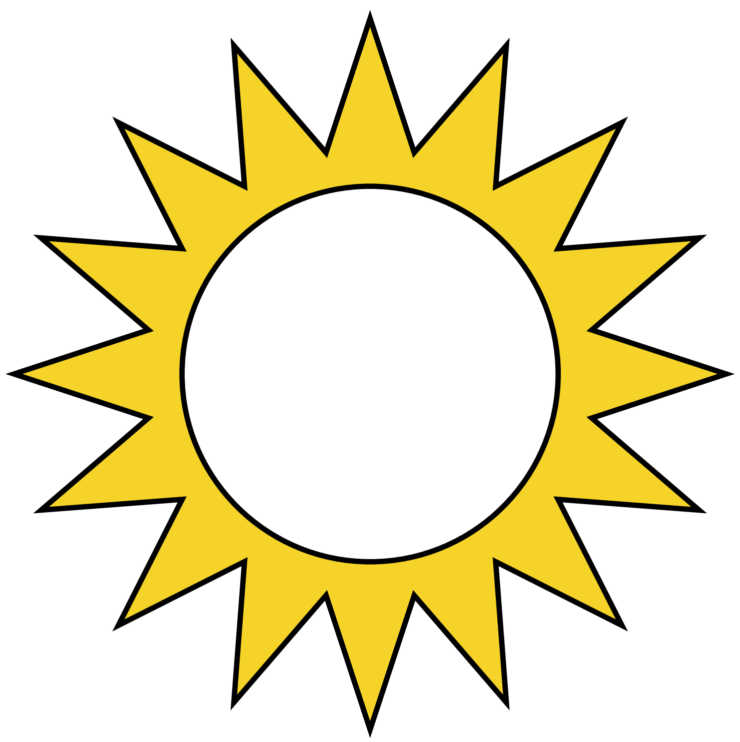
Peculiarities of the strong force

- For both gravity and electromagnetism, the forces decrease the further the objects are separated
- But the strong force gets stronger the further that particles separate, just like a rubber band



The Weak Force

- Weak force acts on both charged and neutral particles
- Special feature: only force which can change particles from one flavour to another
- Carriers of the weak force are the W and Z bosons
- Has a short-range because the W and Z bosons are heavy
- The sun shines because of the weak force

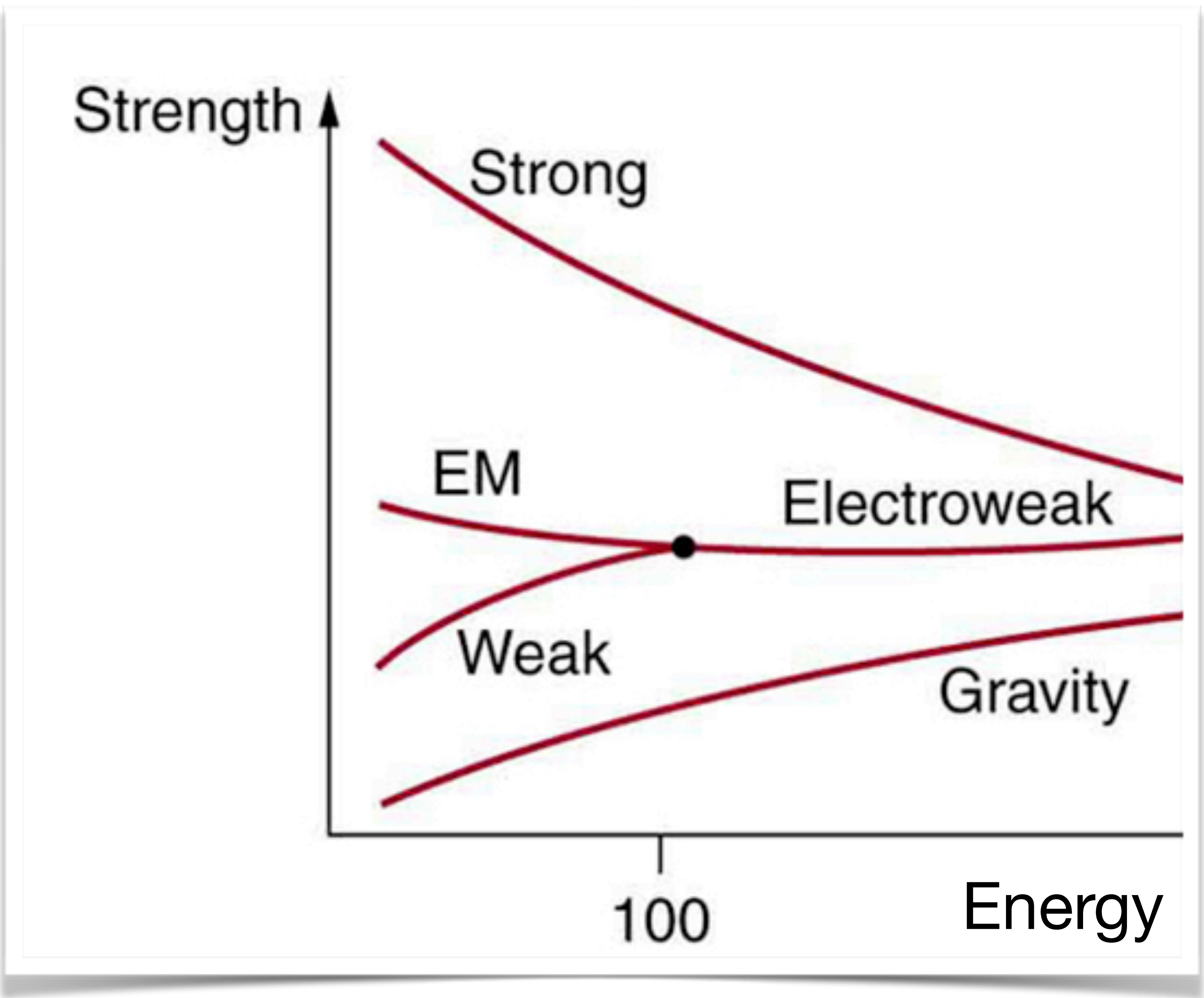


Relative strength of the forces

- At a distance of 10^{-15} meters,
  - 137 x electromagnetic force,
  - 10^{6} x weak force
  - 10^{38} x gravity
- Imagine that apple falling from the tree but accelerating 10^{38} times as quickly
  - that's how it would be if gravity was as strong as the strong force

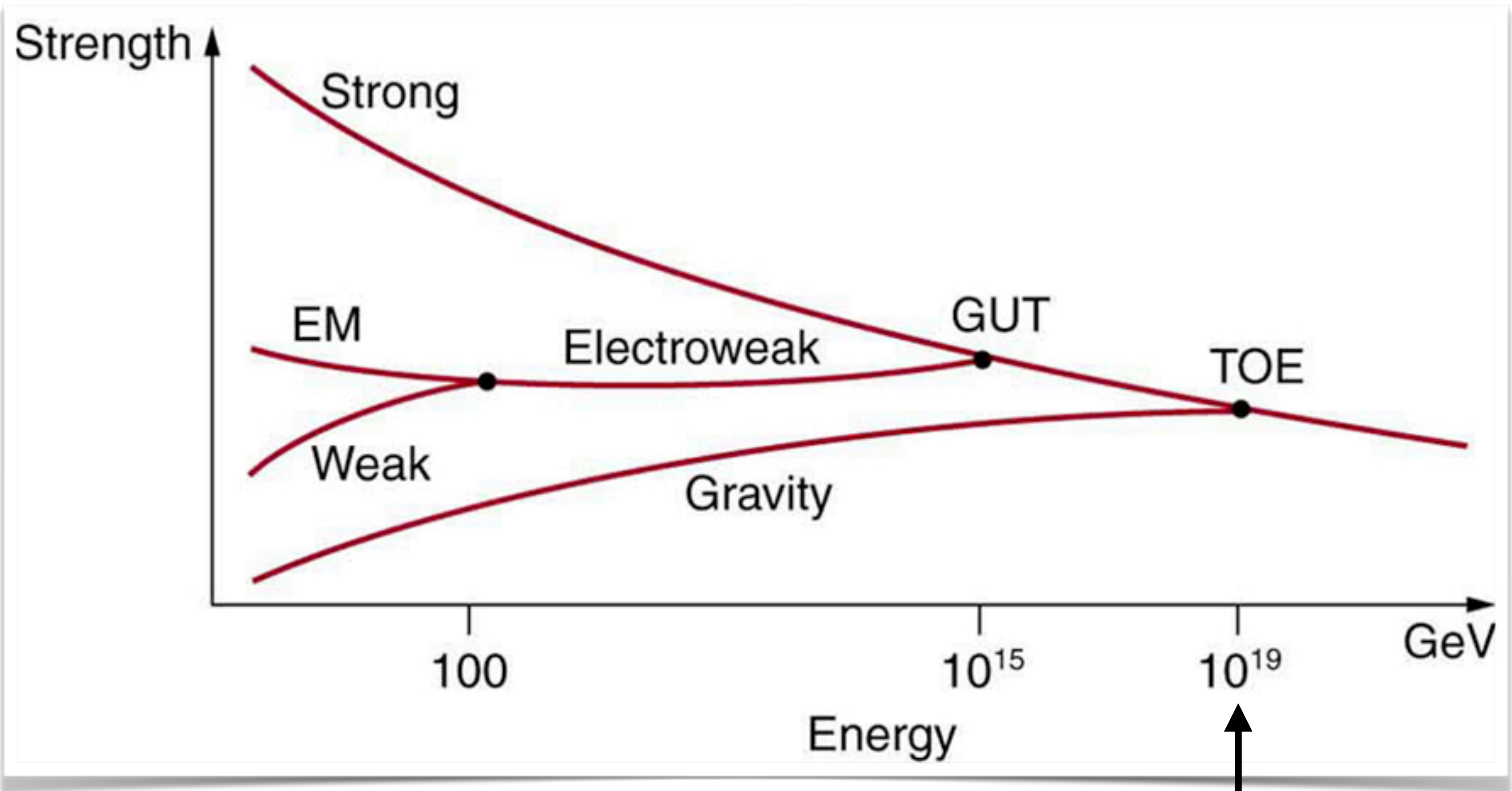
Unification

In the 70s we learnt that the electromagnetic and weak forces unify to become one force above a certain energy



Is there only one force at high energies?

Unification



Planck scale

$$m_P = \sqrt{\frac{\hbar c}{G}}$$

0.02 mg = mass of a flea egg

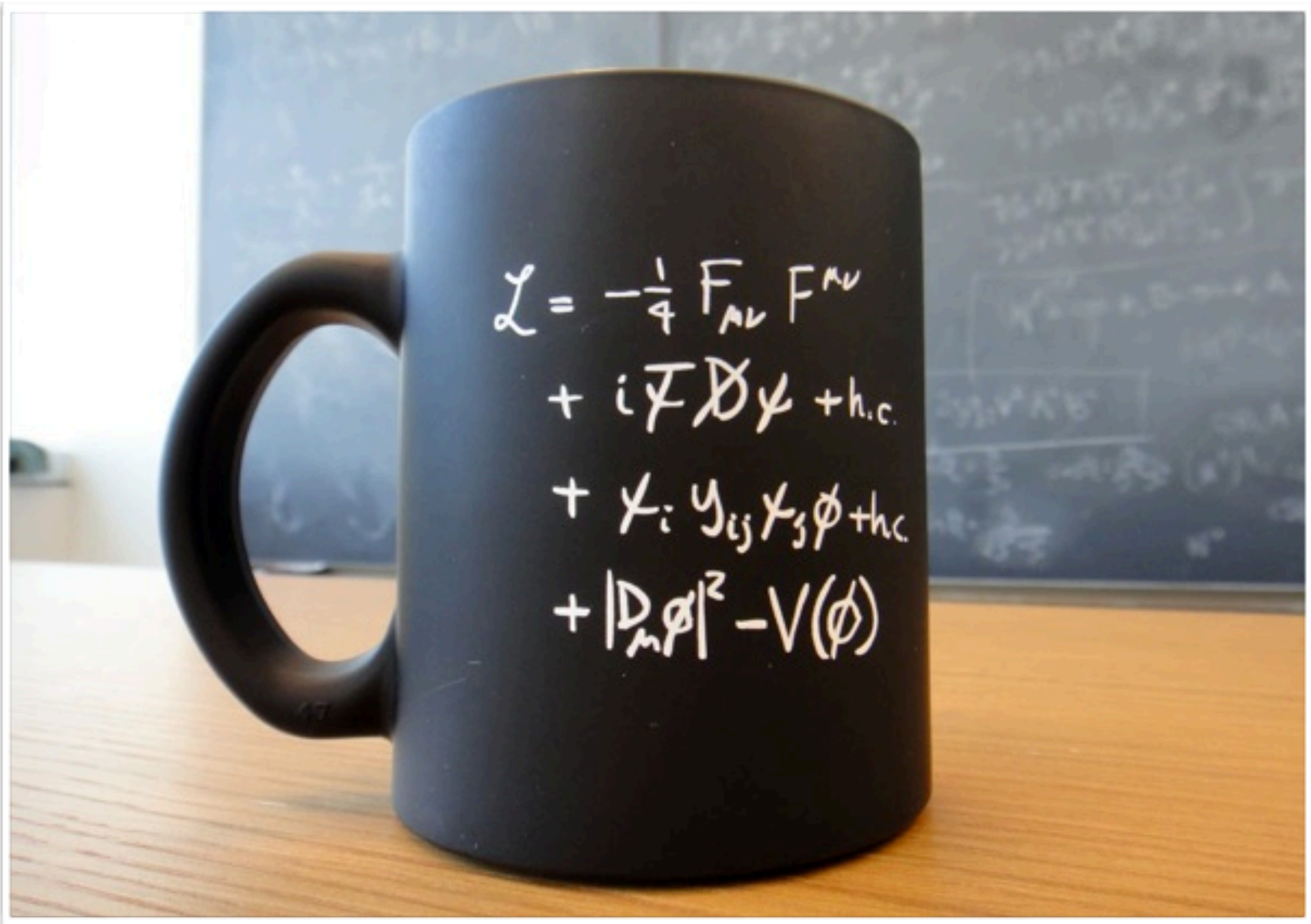
Putting it together: the Standard Model

Quarks

Forces

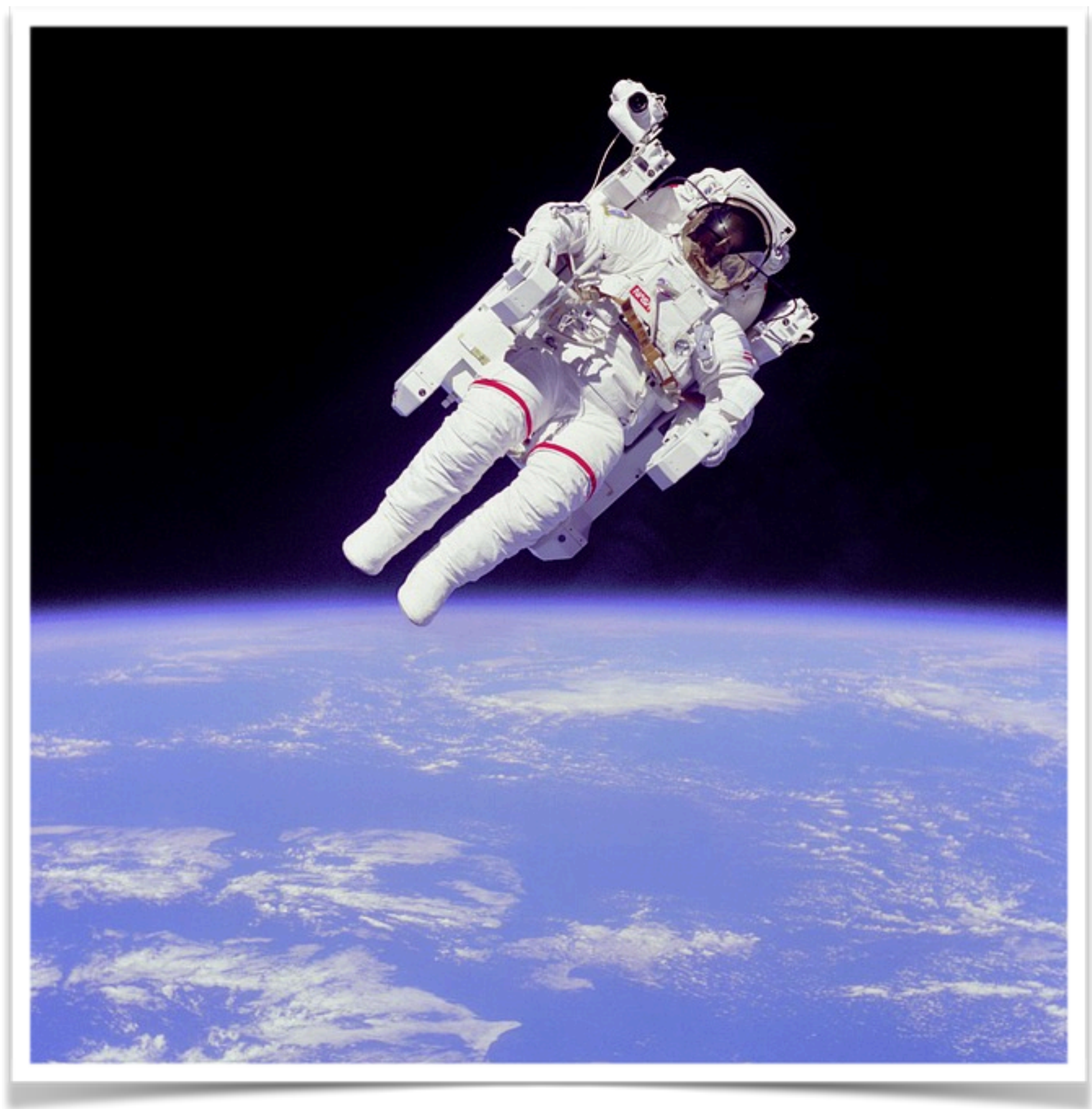
Leptons

The Standard Model

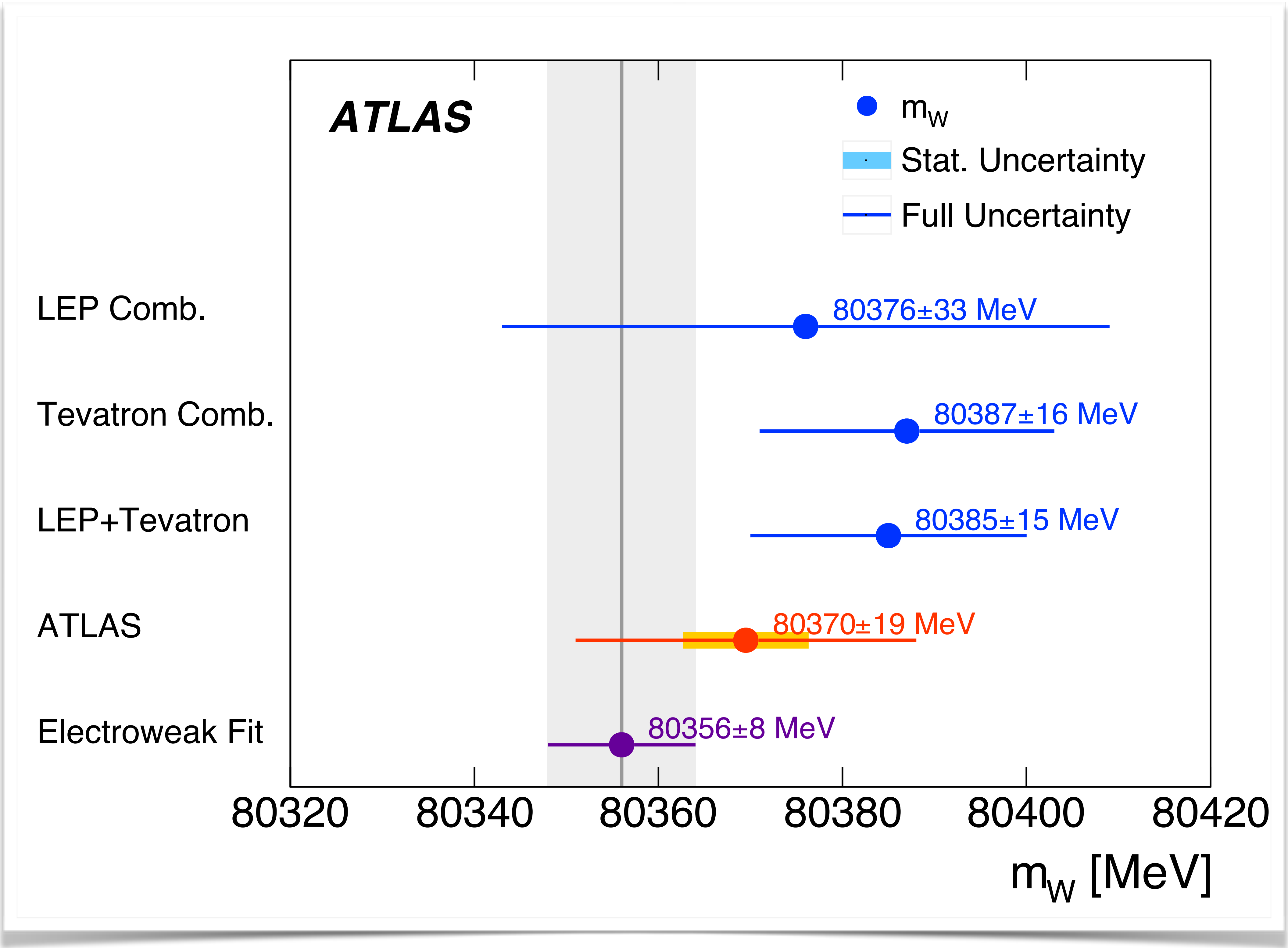


In ~~mug~~ equation form

The Standard Model equations would work perfectly if all particles were massless

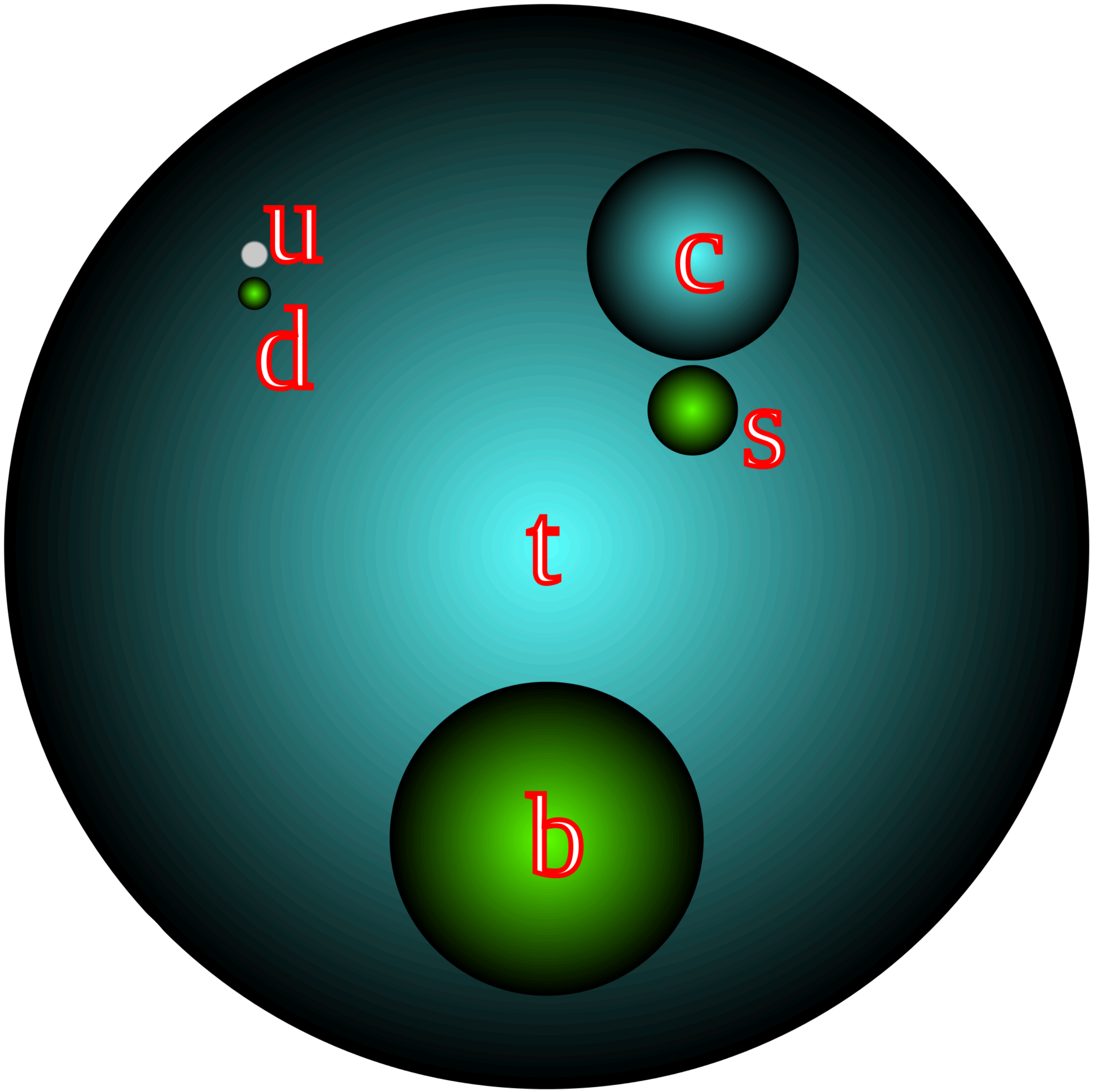


The W Boson has mass !



as does the Z boson

The quarks have (different) mass(es)!

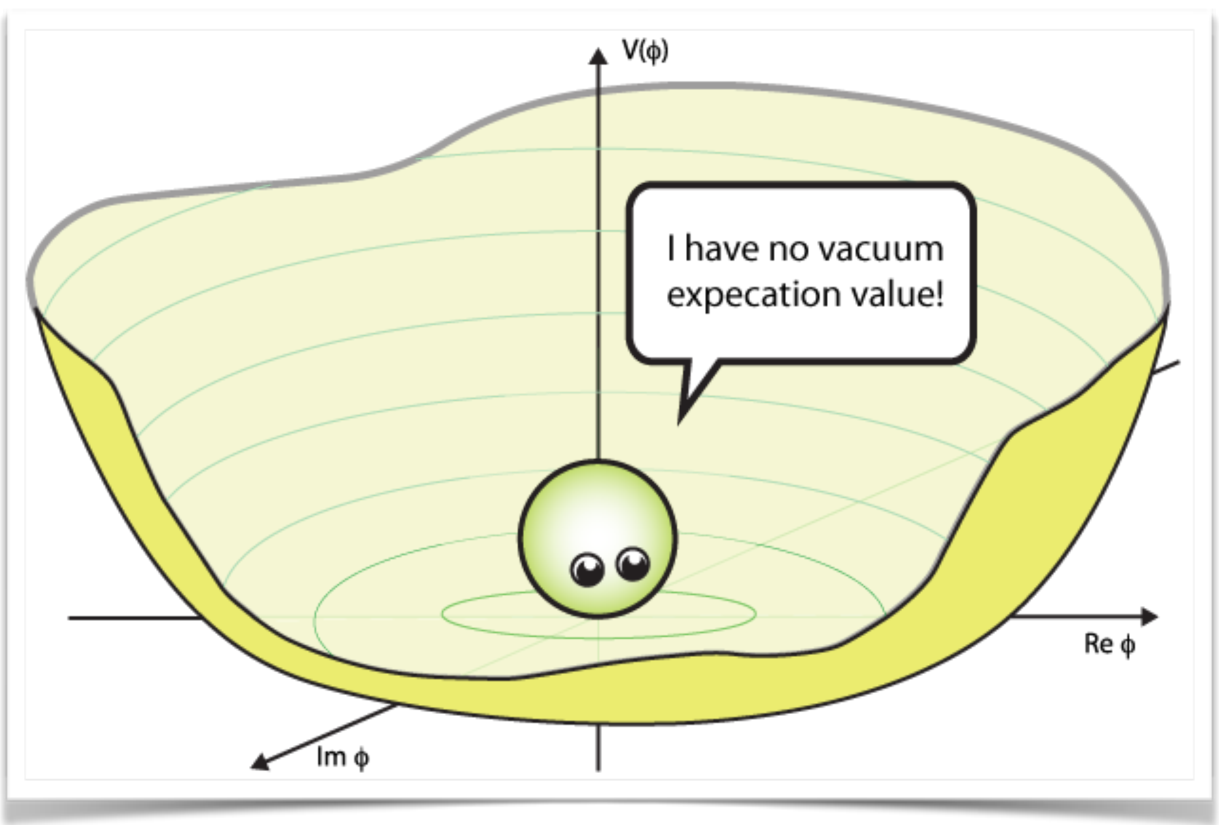


… as do the leptons

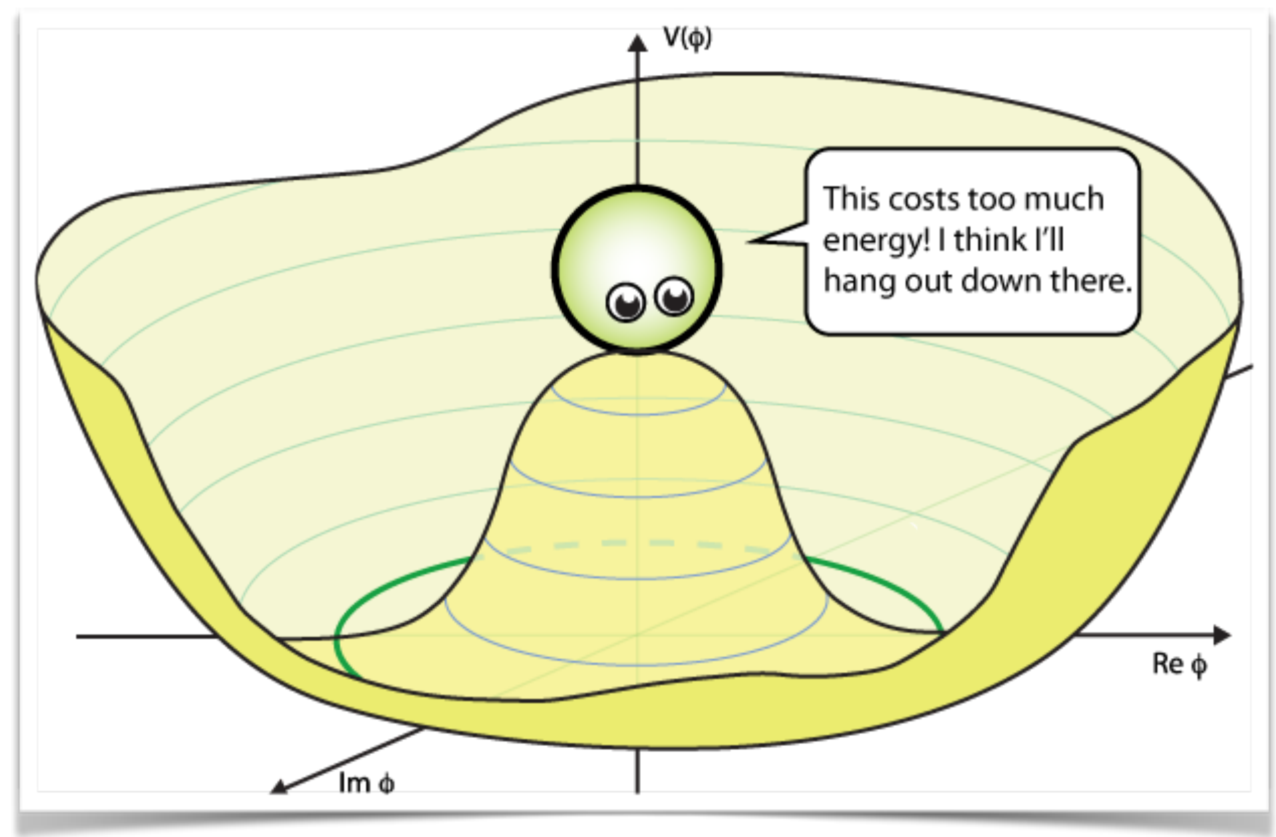
?

The Higgs Boson

Early universe



Today



a mathematical trick

Particle Masses

- A particle's mass is determined by how strongly it interacts with the Higgs field
- Heavier particles interact more strongly
  - OR particles that interact more strongly become heavier

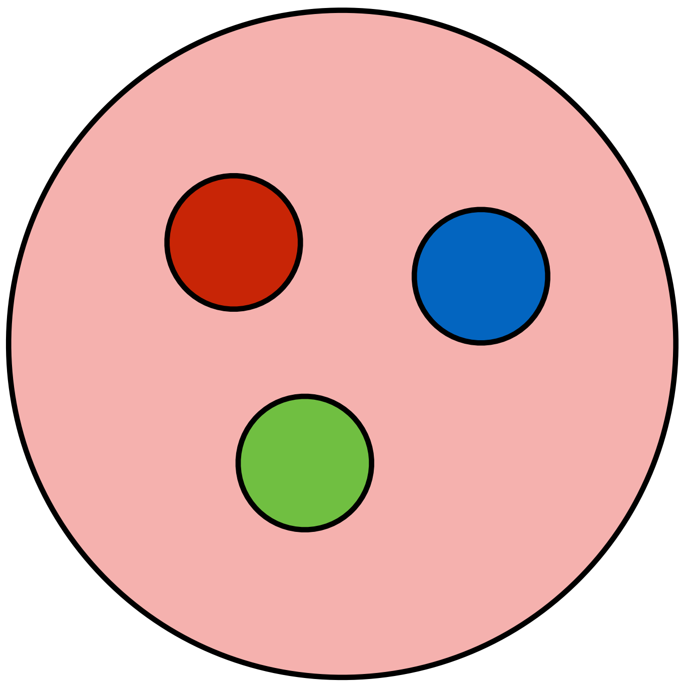
Analogy: Fisk Tank

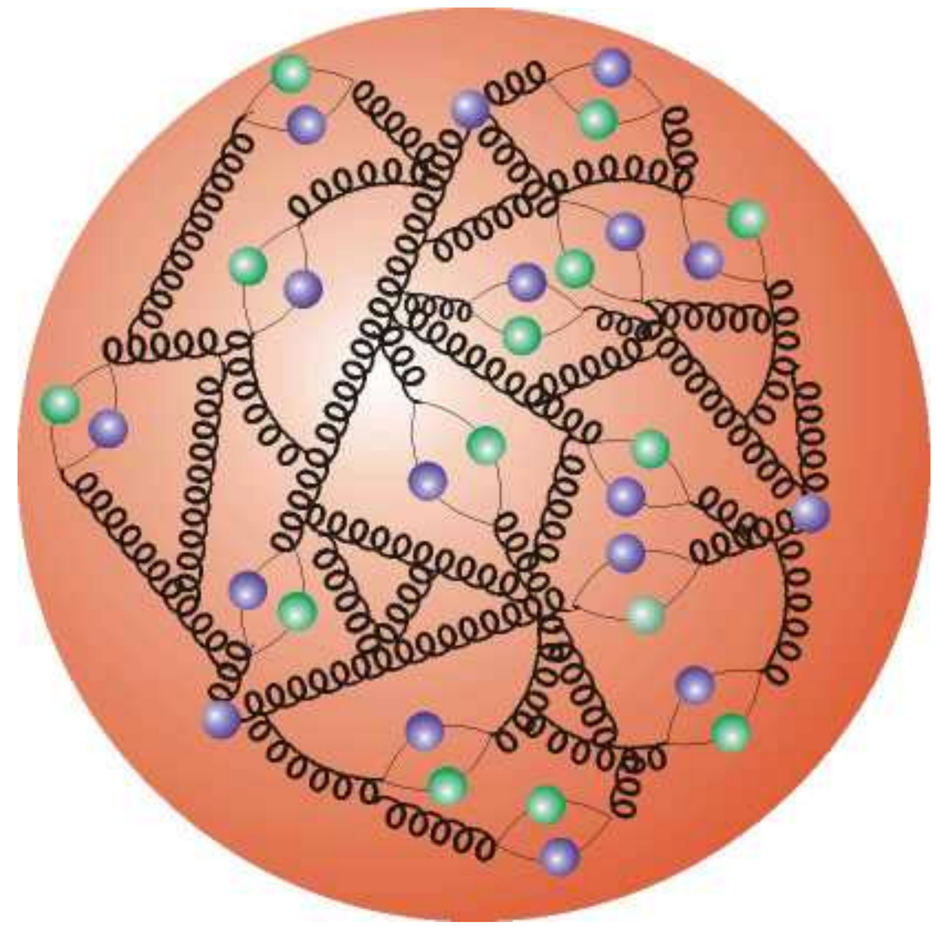
Analogy: Fisk Tank

Can I blame the Higgs for being fat?

No!

Mass of three quarks = 0.2% proton mass





Remaining 99.8% from the gluons binding the proton together!

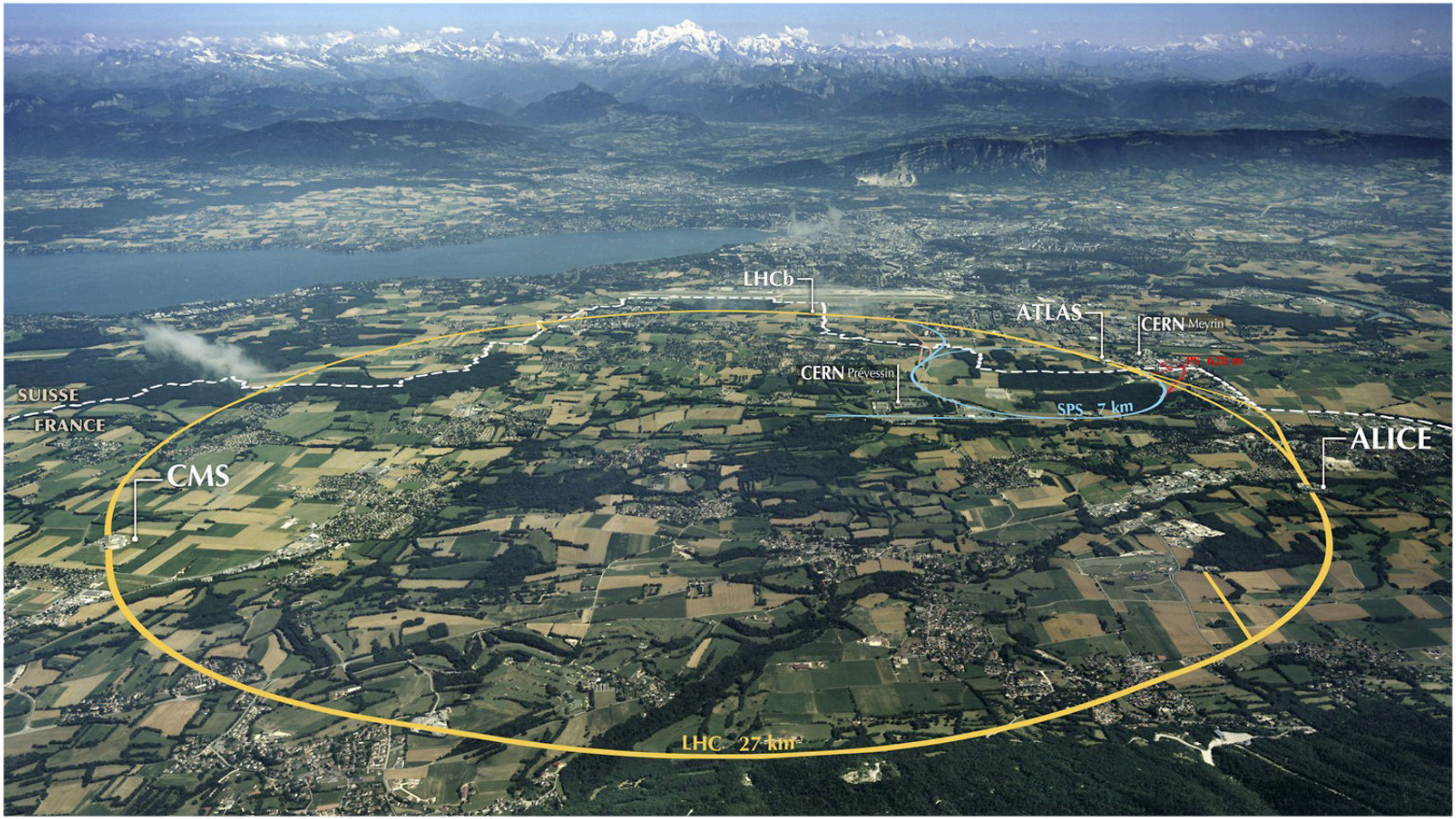
Bonus: How do we make and study these particles?

Microscopes

See tiny objects by magnifying the light they produce

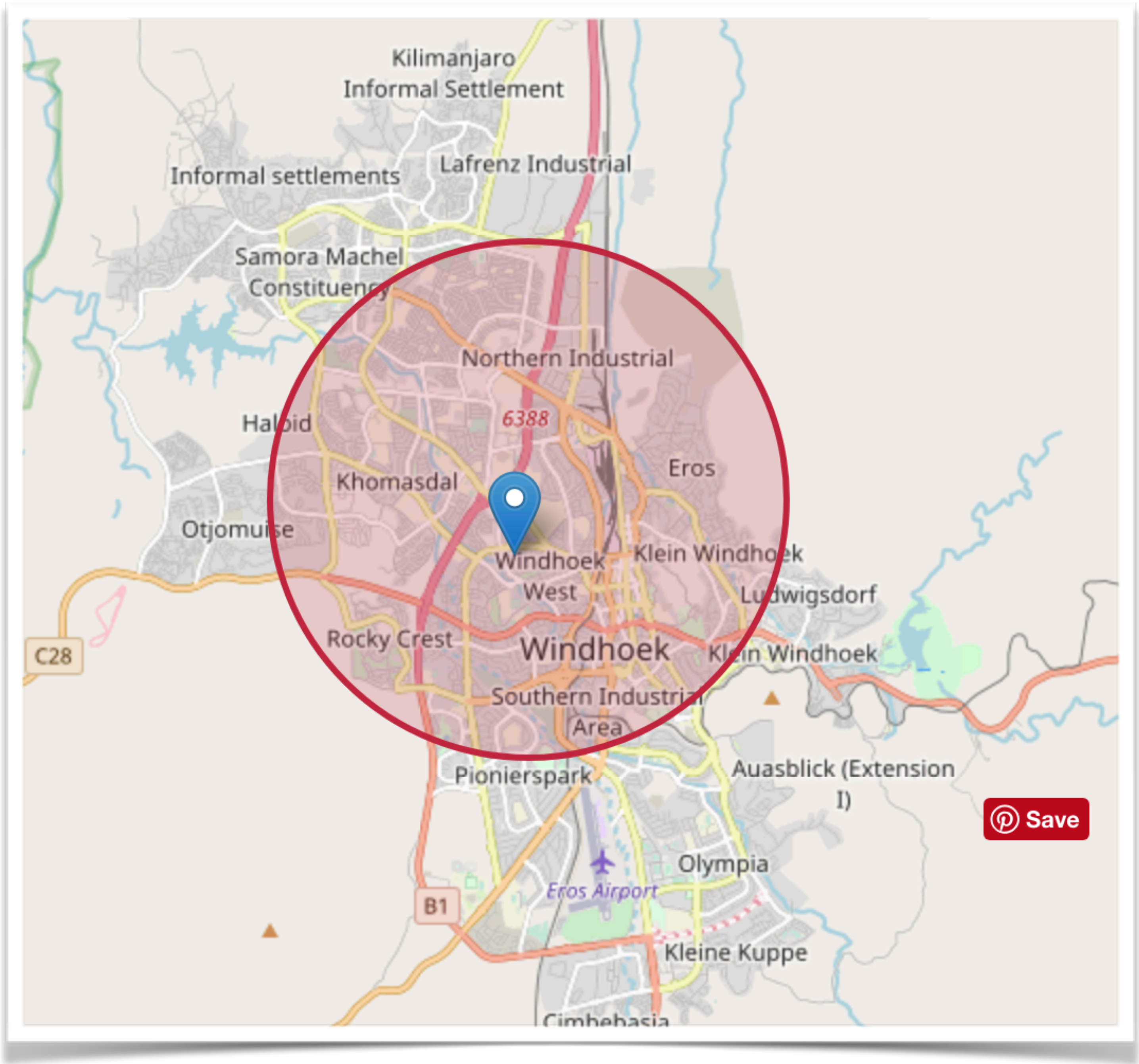
Our biggest microscope:

The Large Hadron Collider



How big is the LHC?

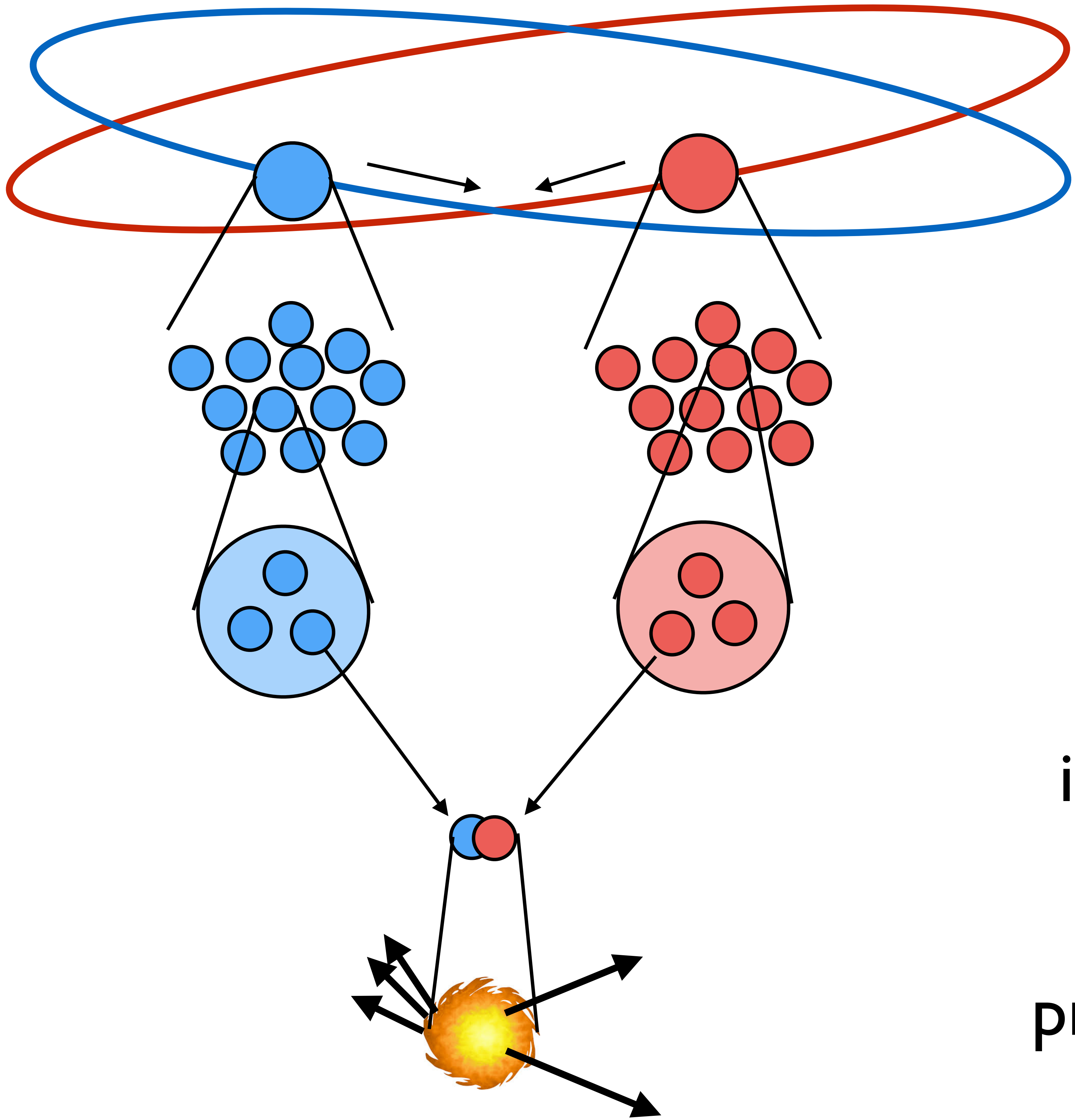
A 27 km long collider near Geneva, Switzerland



(Would cover most of Windhoek)

Source: https://natronics.github.io/science-hack-day-2014/lhc-map/

Collider basics



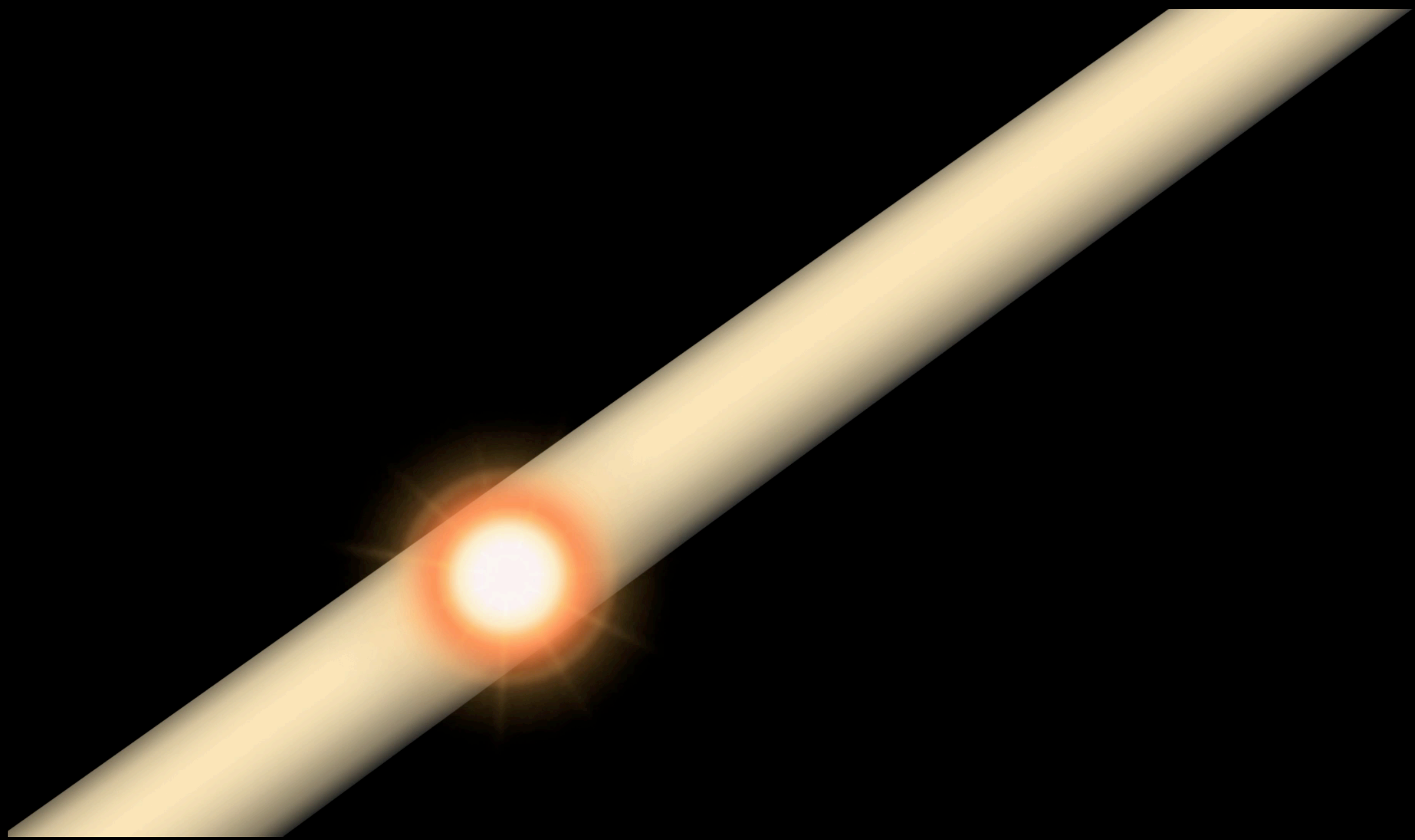
proton beams

bunches

colliding protons

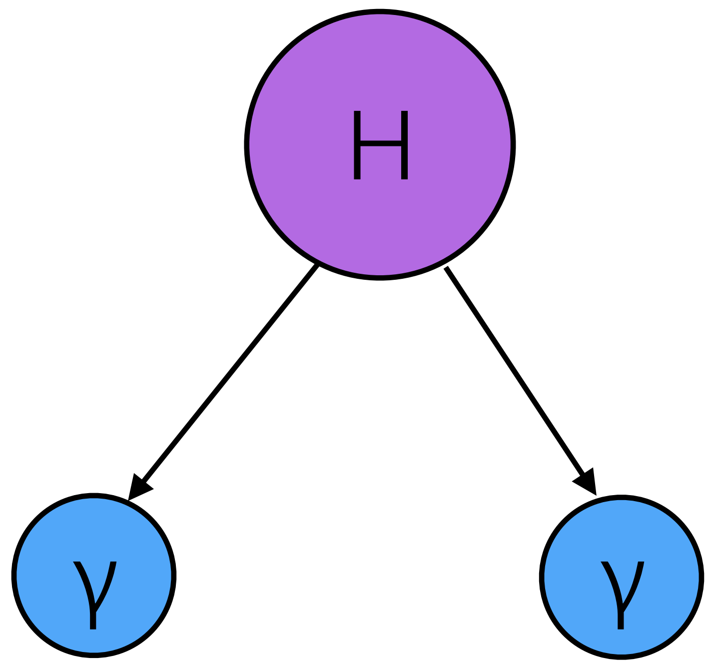
interacting quarks
(or gluons)

produce and decay
new particles



Seeing particles: e.g. the Higgs

Highly unstable elementary particle!
Lifetime is only 1.6×10^{-22} s



See the Higgs and other unstable elementary particles by studying the particles that are produced when they decay

How do we measure the particles we produce … detectors !

Energy and mass

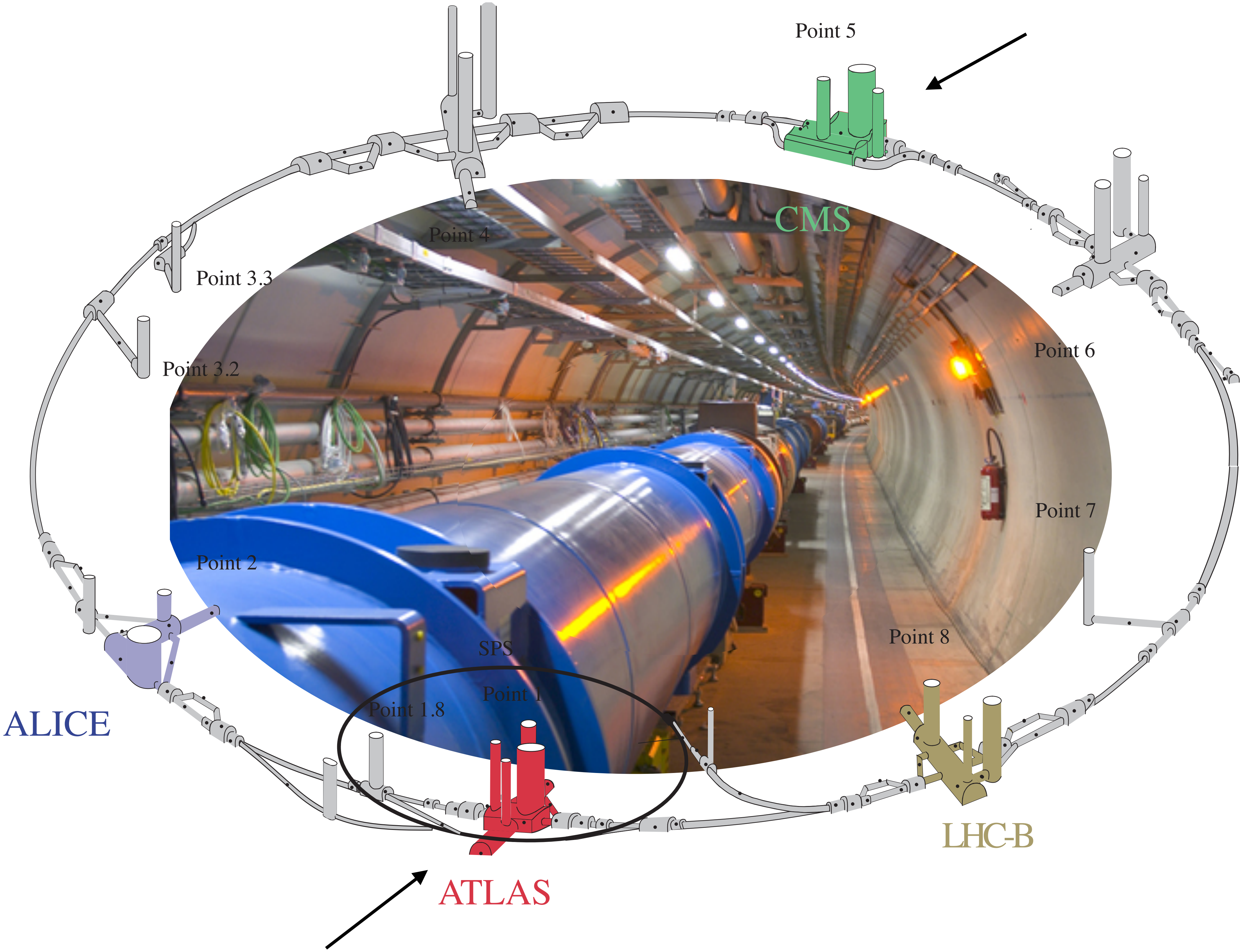
A very famous equation:

$$E = mc^2$$

Deep relationship between energy and mass

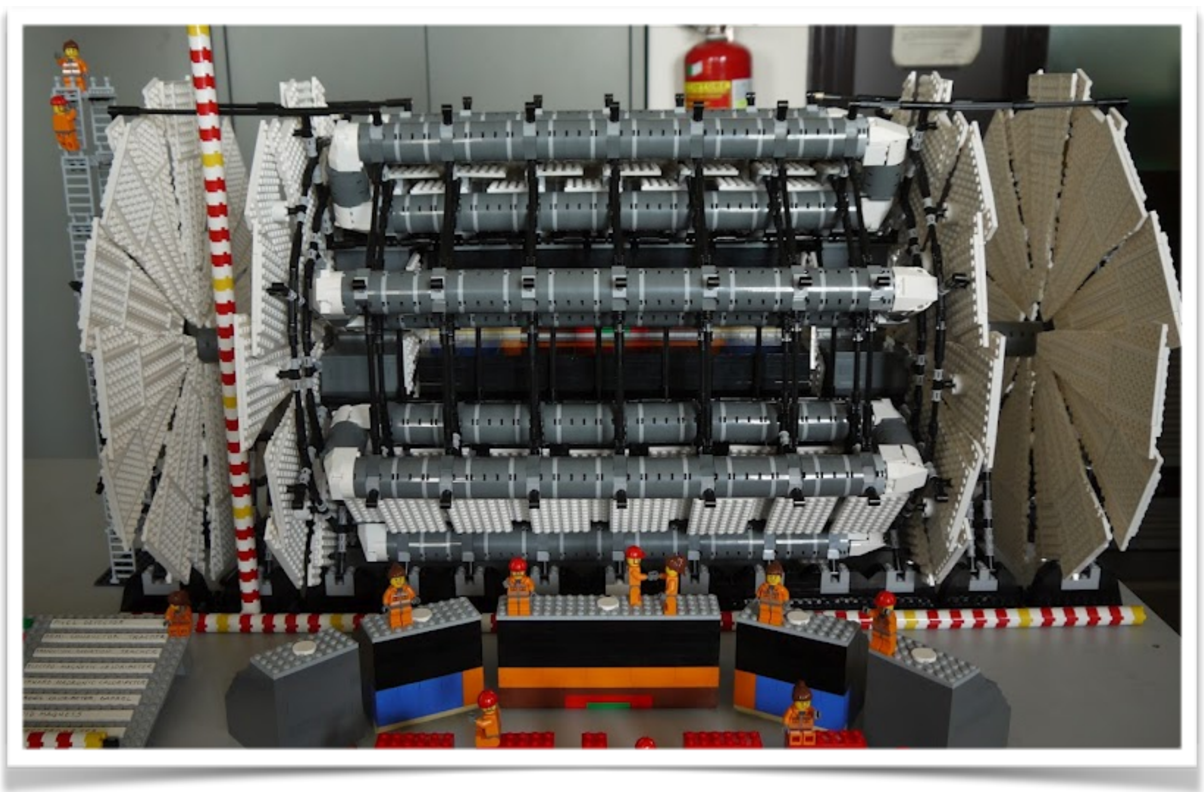
Practically, what it means is that when we collide very high energy particles, we can use their energy to produce new massive particles

The LHC and its experiments

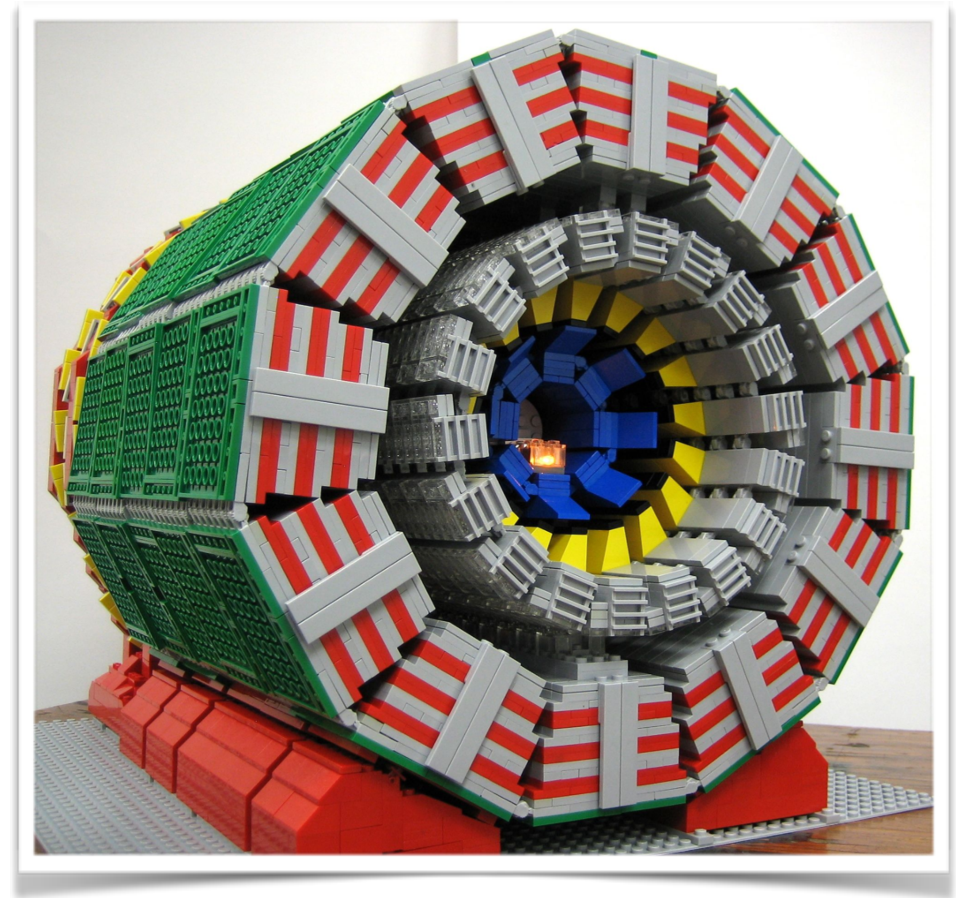


The Detectors

ATLAS



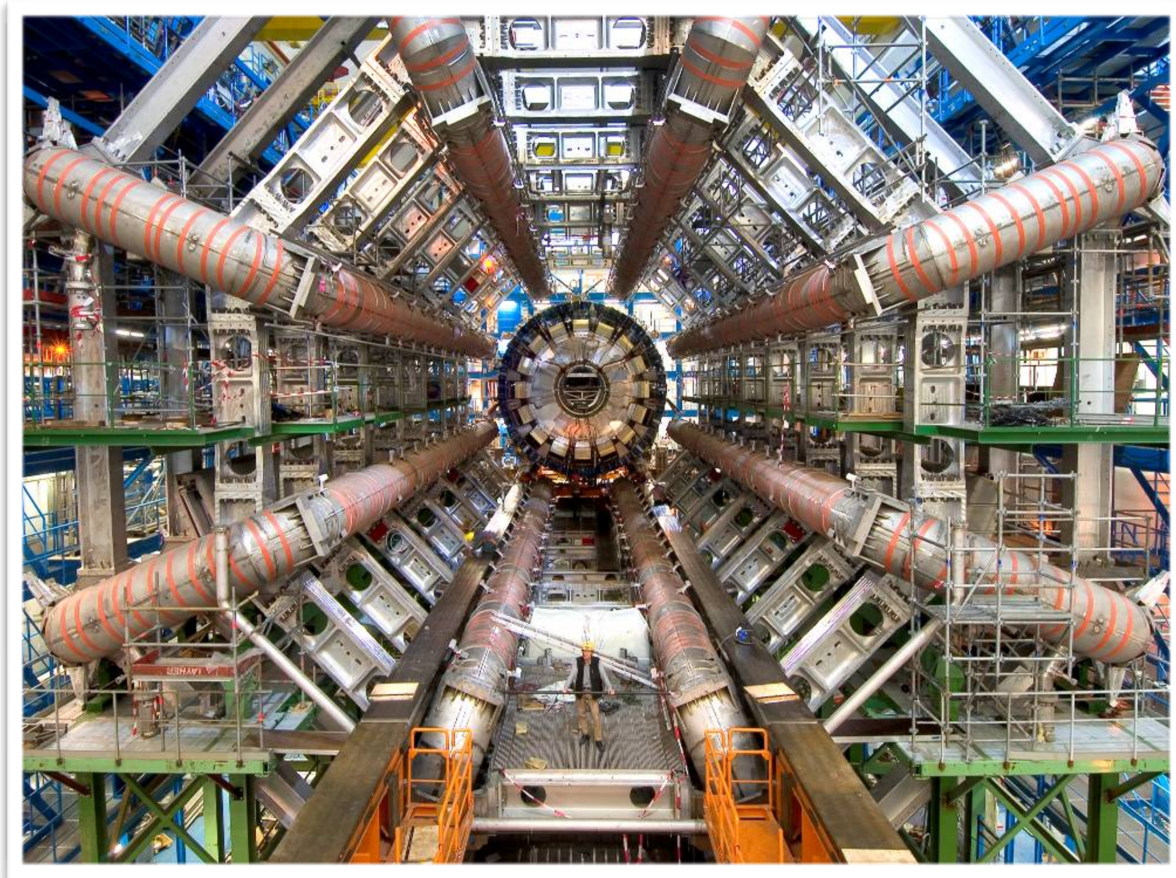
CMS



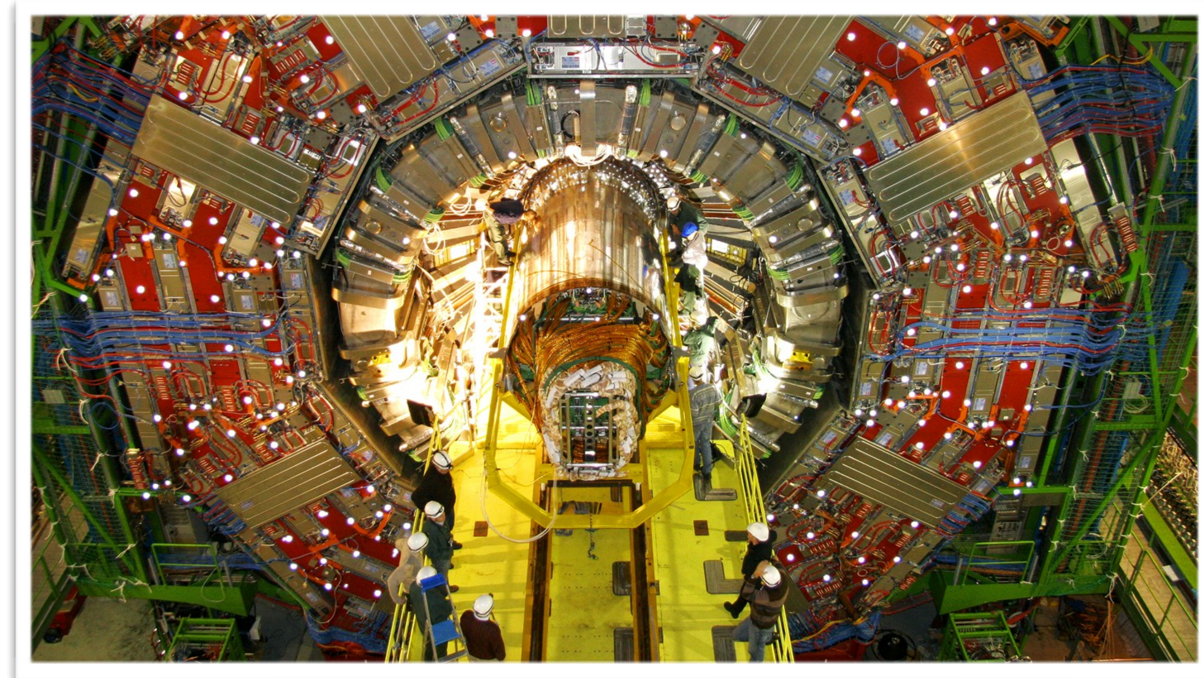
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

The Detectors

ATLAS



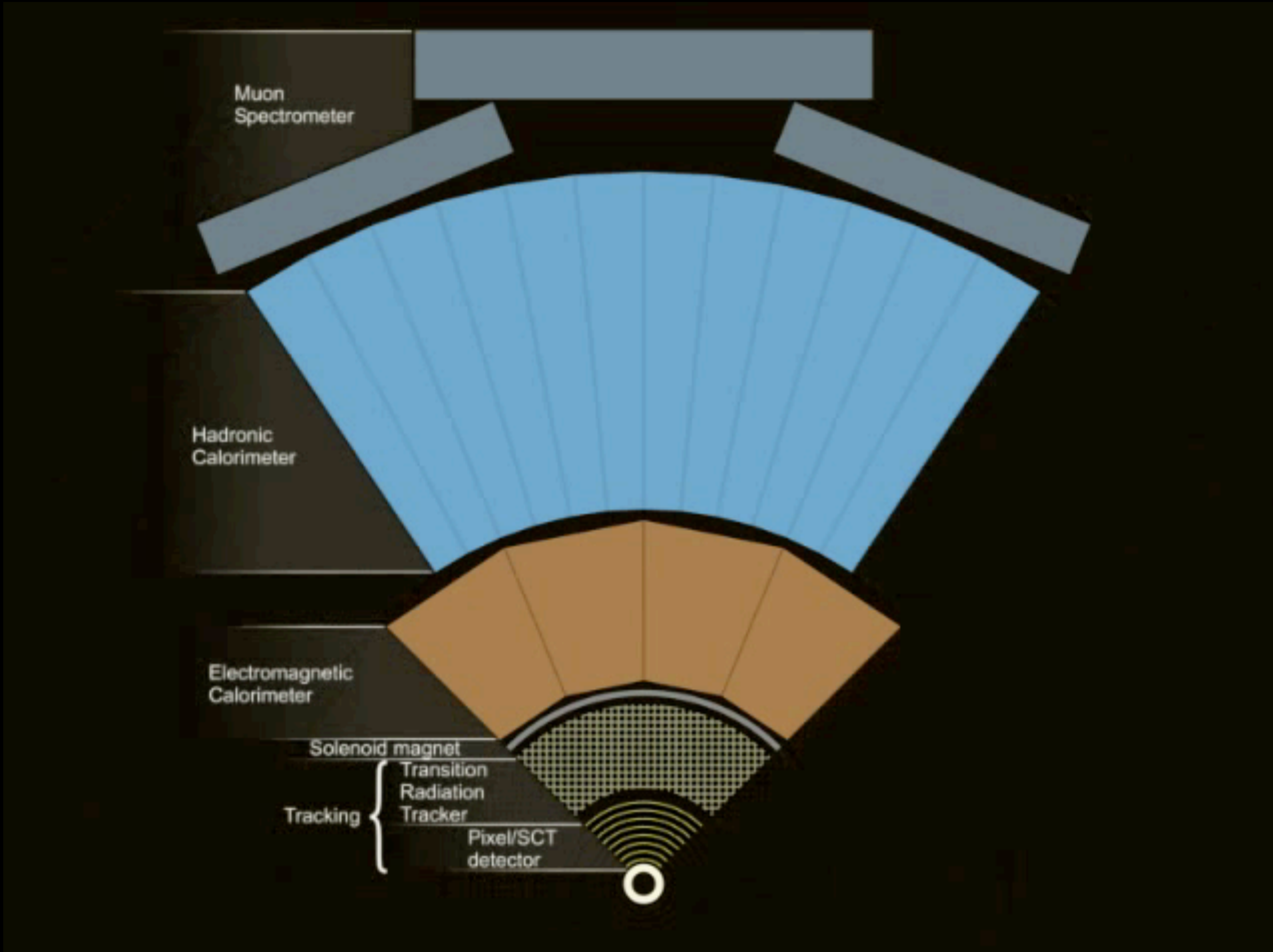
CMS



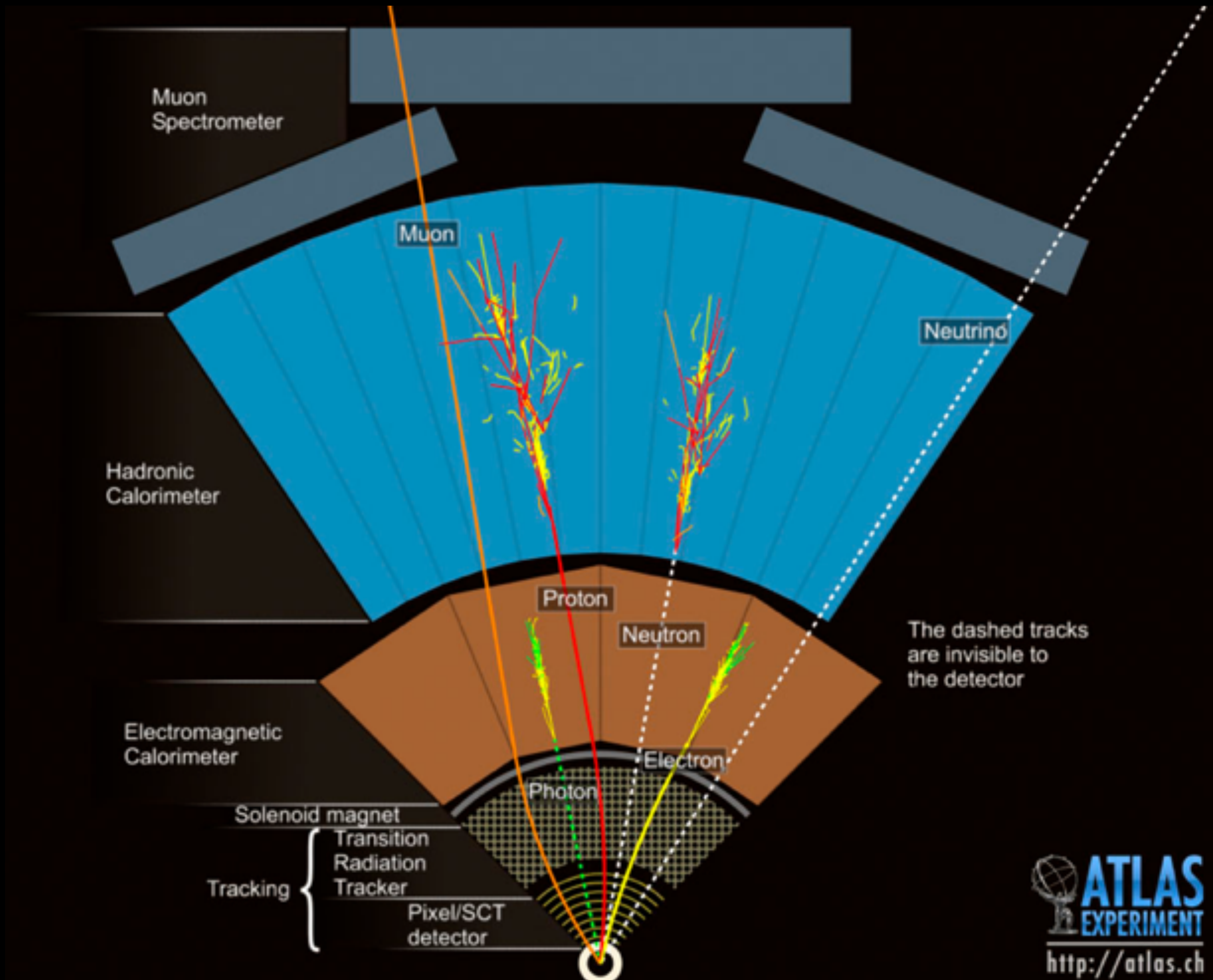
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

Particle Detectors are like onions

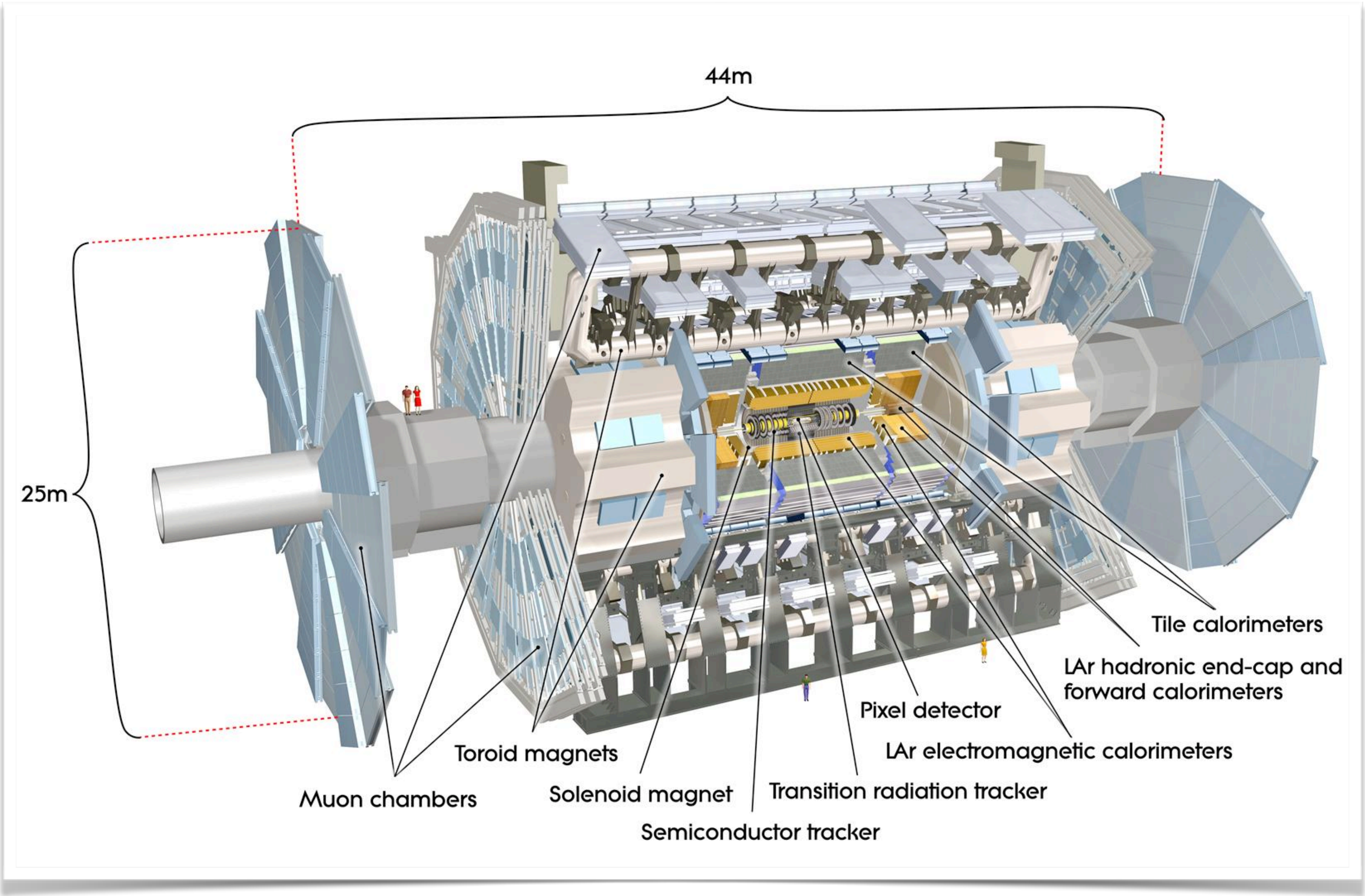
Different technologies in different layers to detect different particles: electrons, photons, protons, neutrons, “neutrinos”



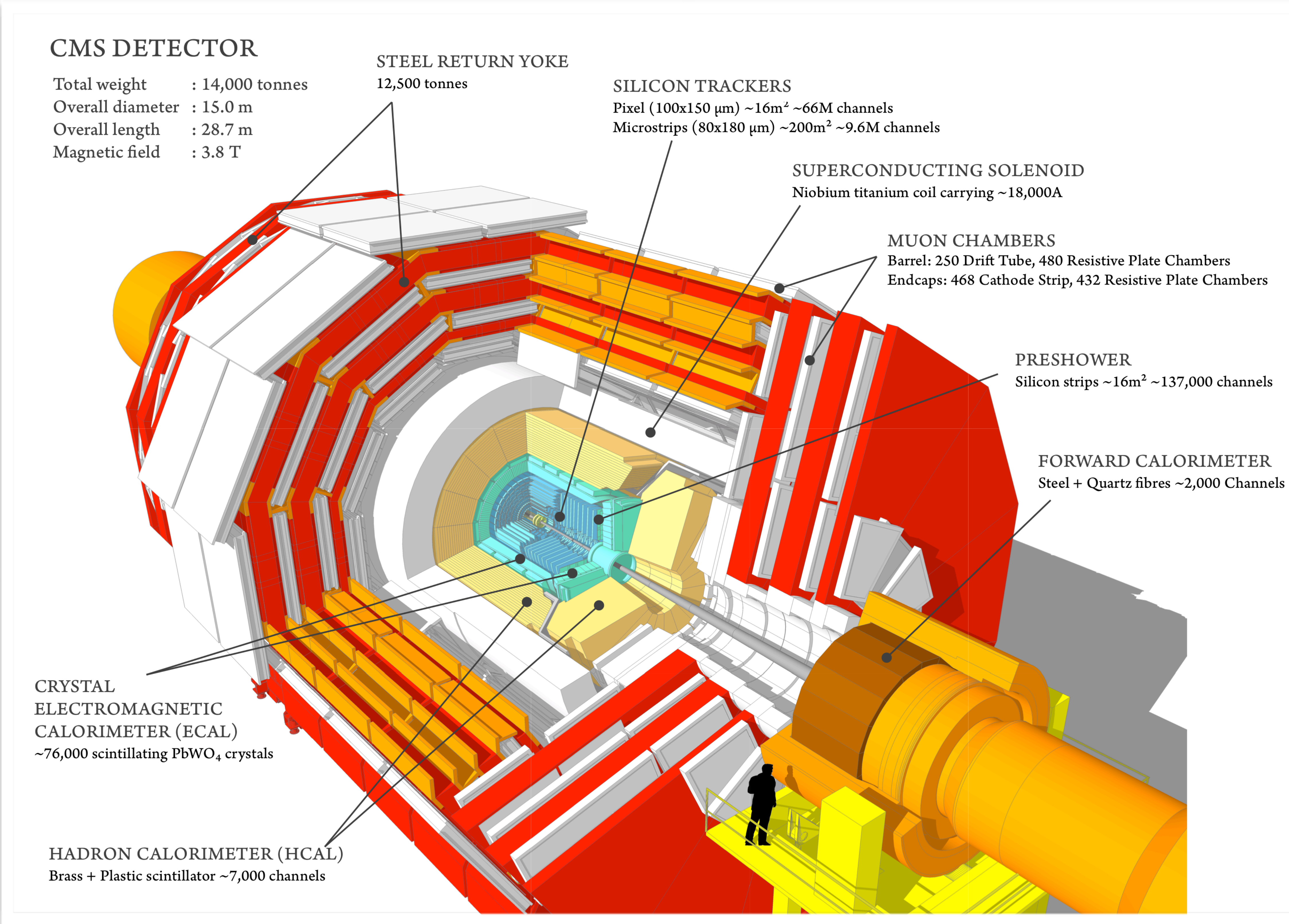
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch

A Large Toroidal ApparatuS (ATLAS)

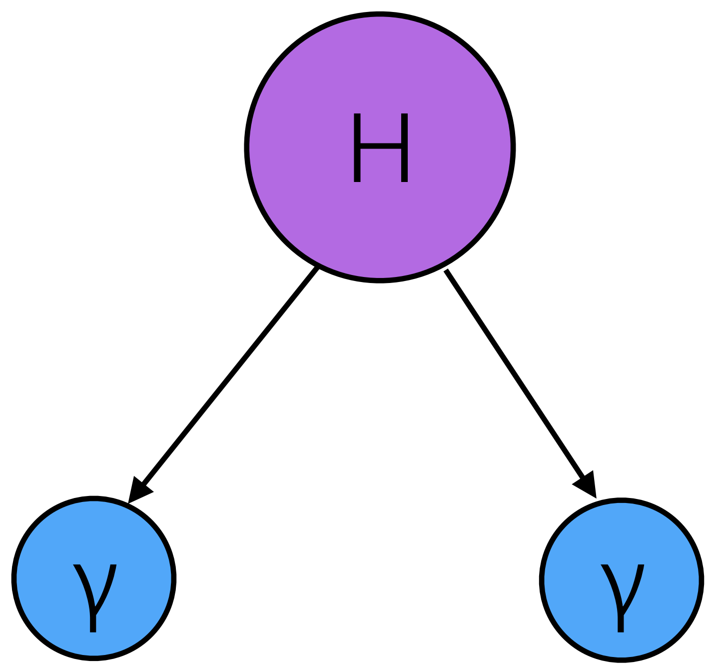


The Compact Muon Solenoid (CMS)



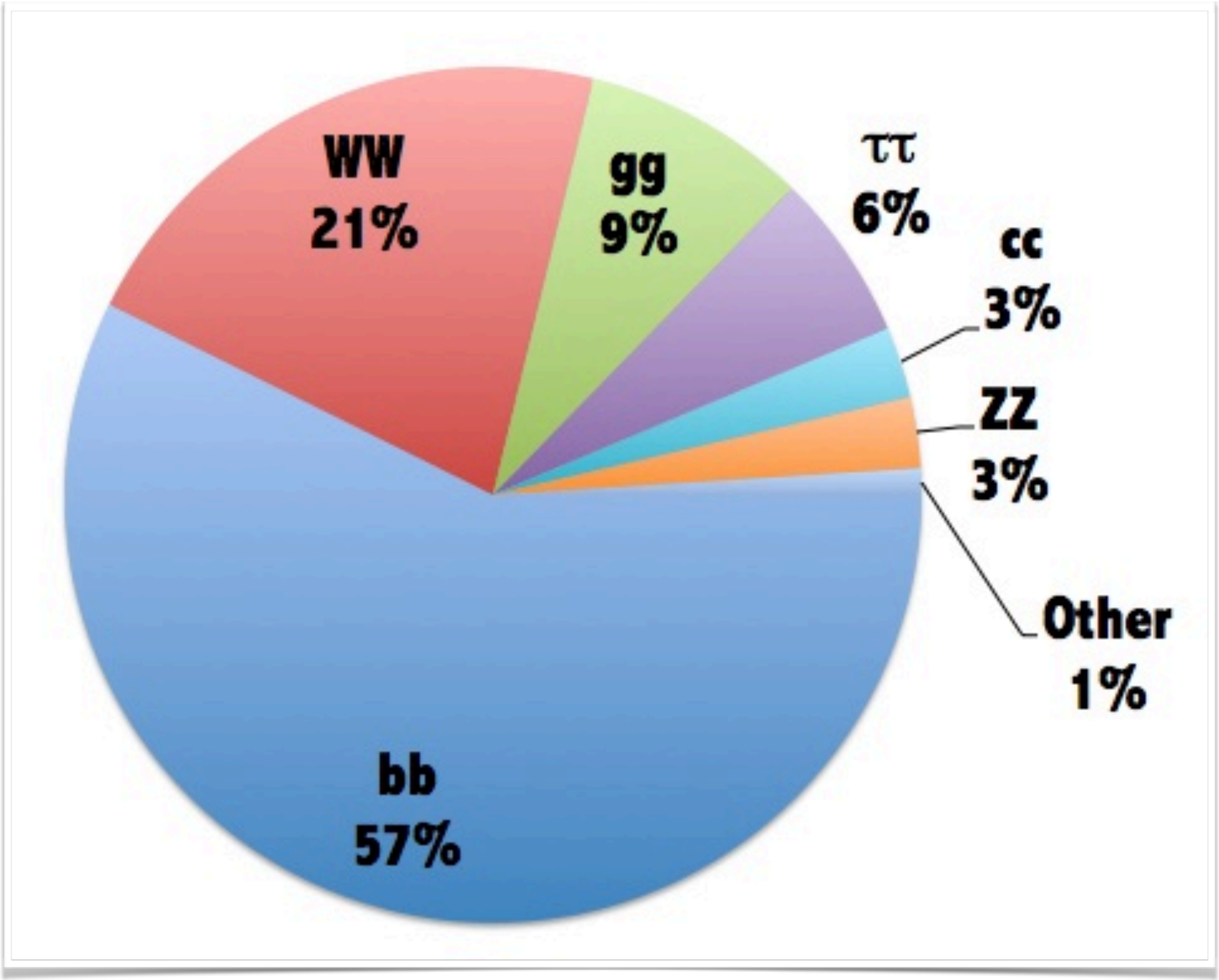
Seeing particles: e.g the Higgs

Highly unstable elementary particle!
Lifetime is only 1.6×10^{-22} s



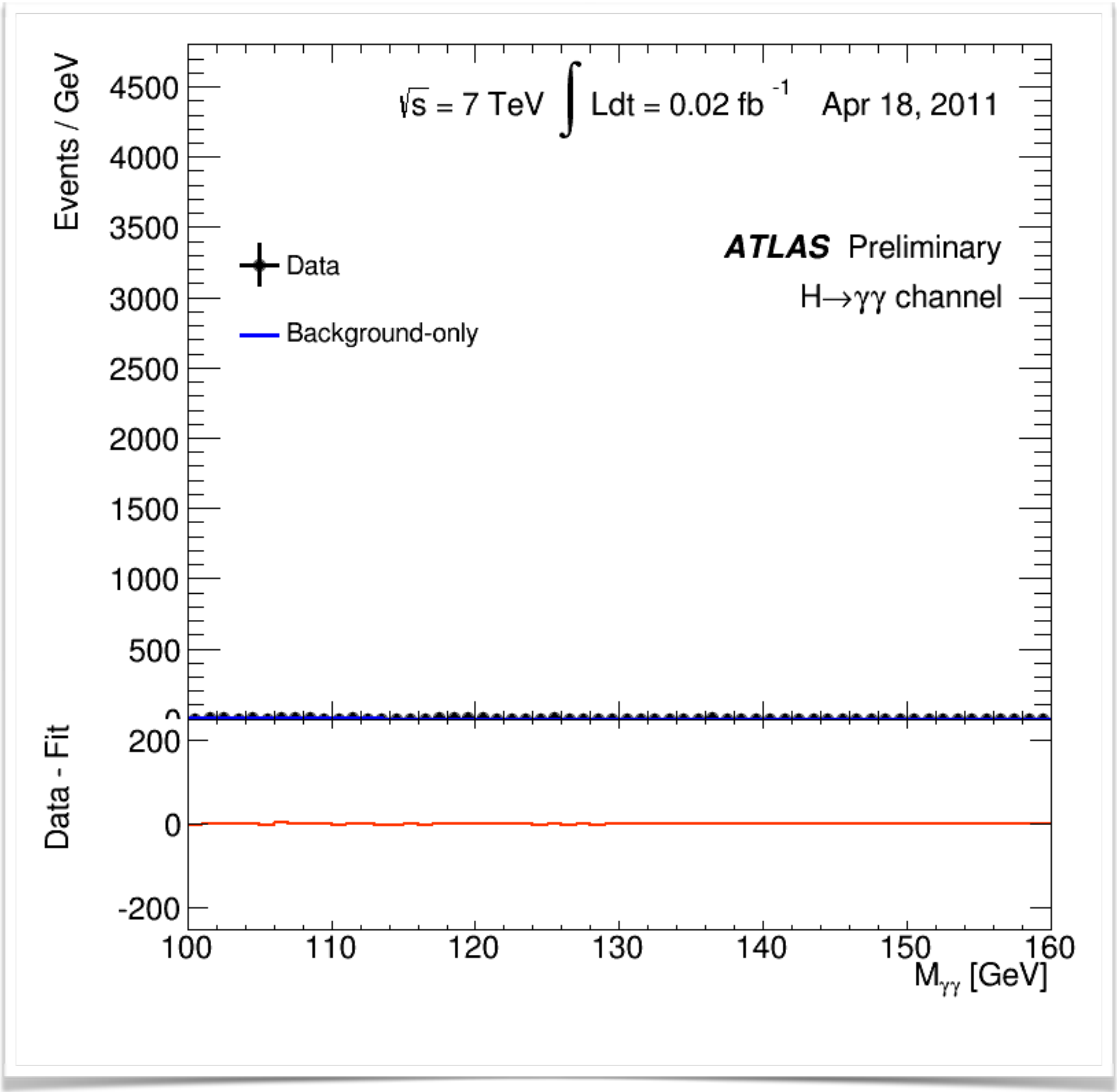
See the Higgs by studying the particles that are produced when it decays

Higgs Decays



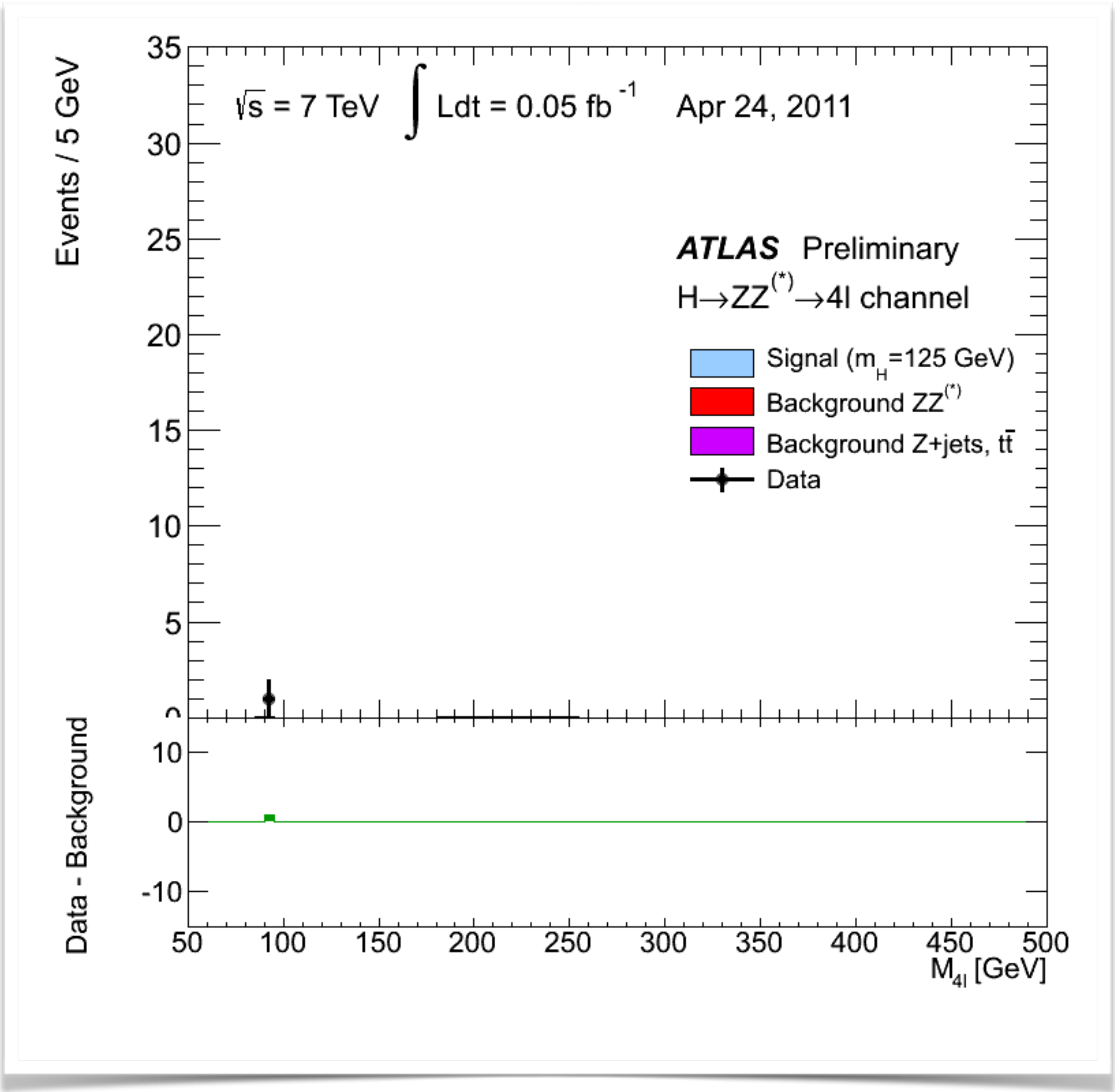
Higgs decays to any particle that has mass

Higgs to two photons ($H \rightarrow \gamma\gamma$)



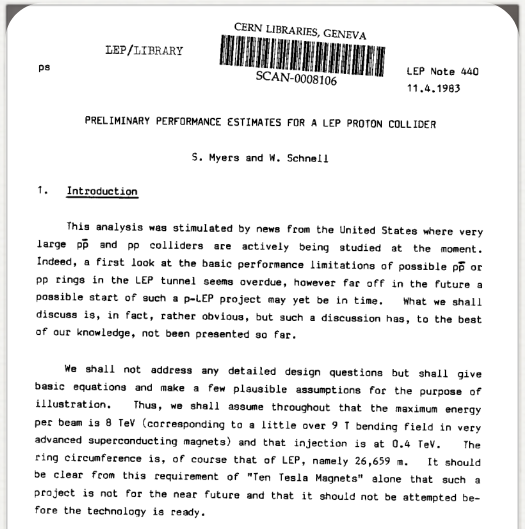
4 July 2012

Higgs to 4 leptons (H→ZZ*→llll)



4 July 2012

4 July 2012: Higgs (In)dependence Day



ps

LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

Duration of projects /planning stability:
First LHC workshop 1984 !

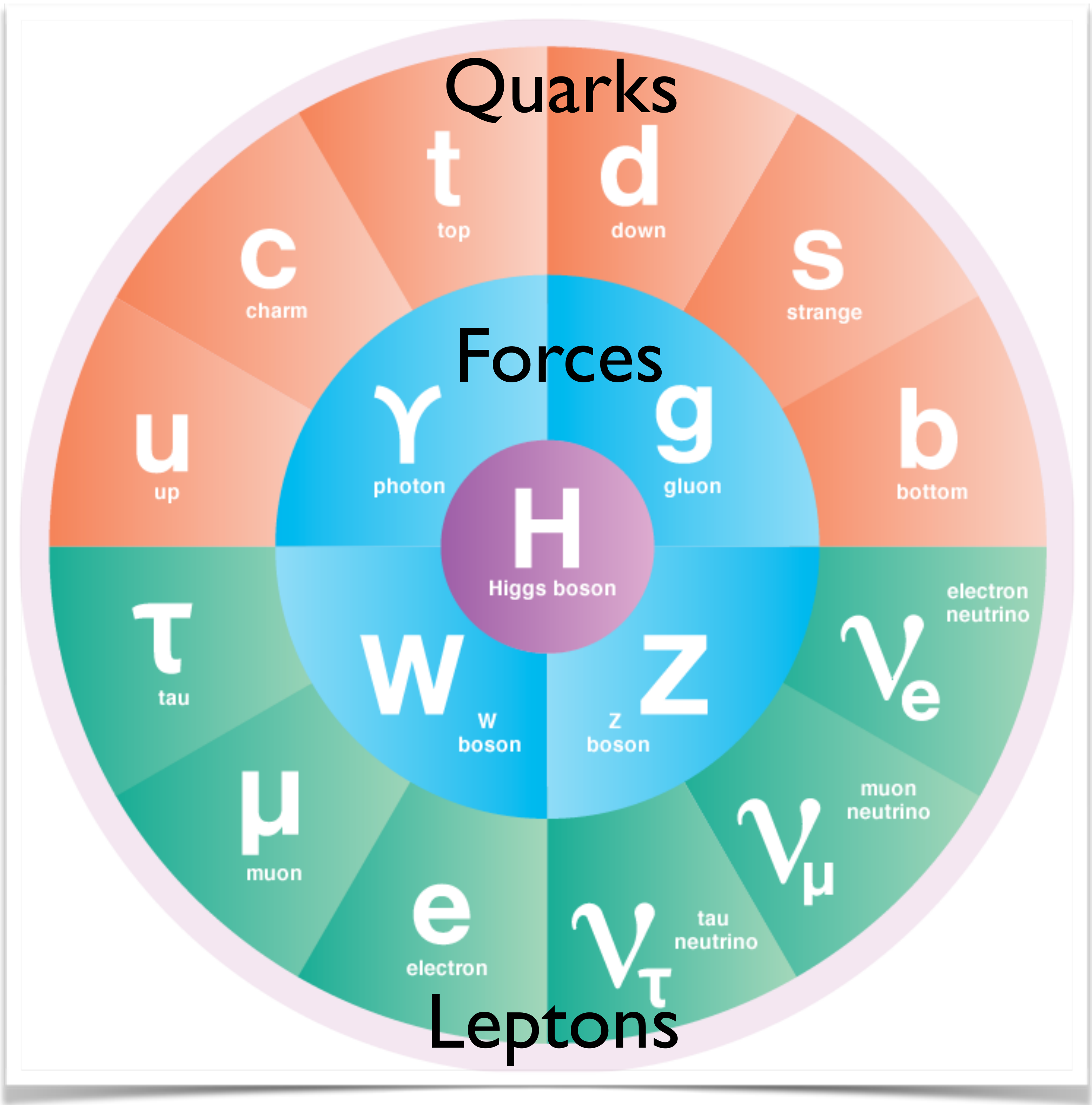
Nobel Prize in Physics 2013

to

Peter Higgs

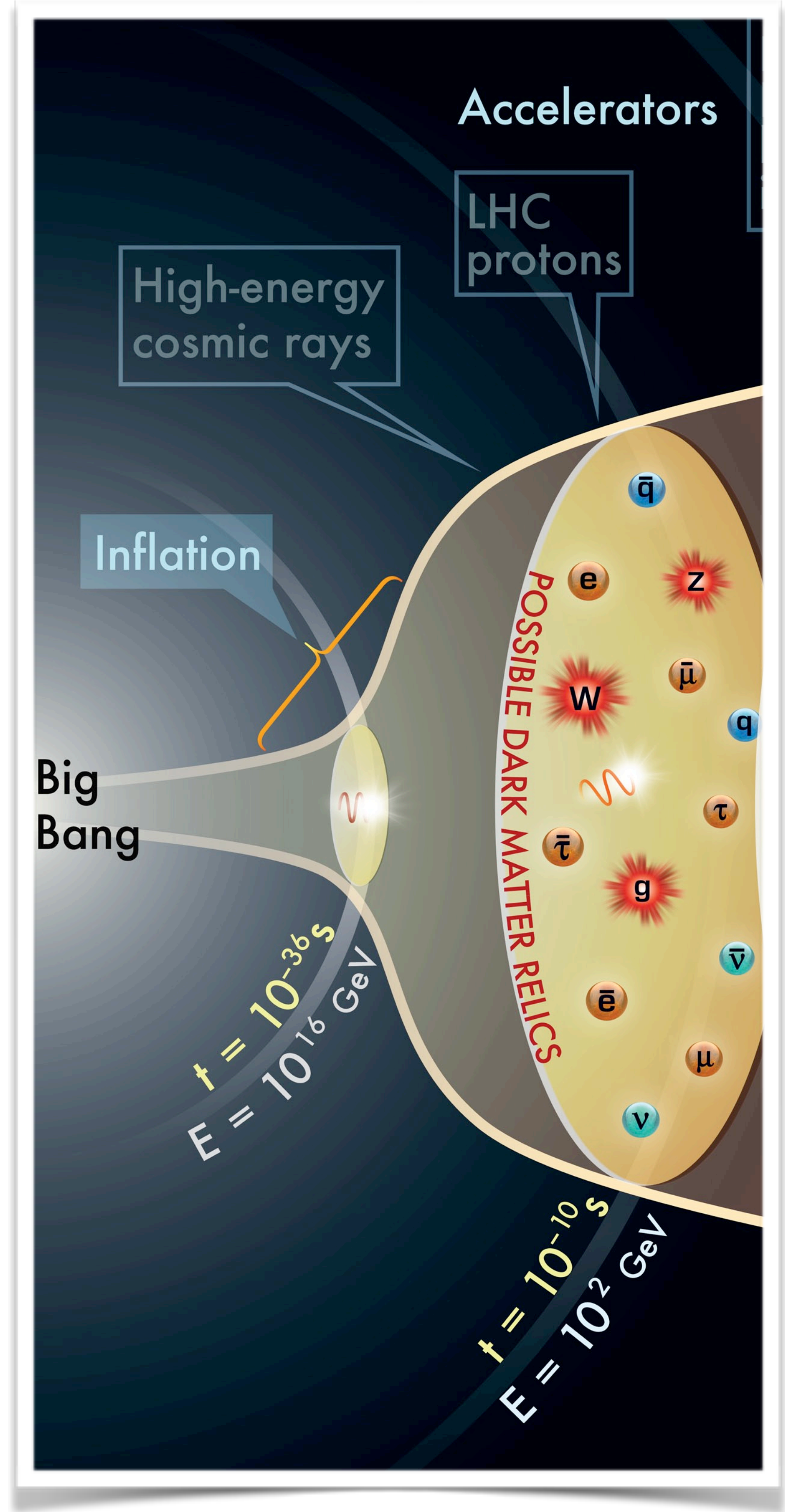
François Englert

The final piece of the Standard Model



But ... many questions remain

- Why do the fermions have such different masses?
- What is dark matter ?
- Why is there so much more matter than antimatter in the universe?
- What happened in the first few moments of the universe ?
  - Did the Higgs play a special role?
- Are there other forces ?



As so often in science, answering one question, opens the door to many more

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