

A brief introduction to “Fundamental Physics”

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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 it 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



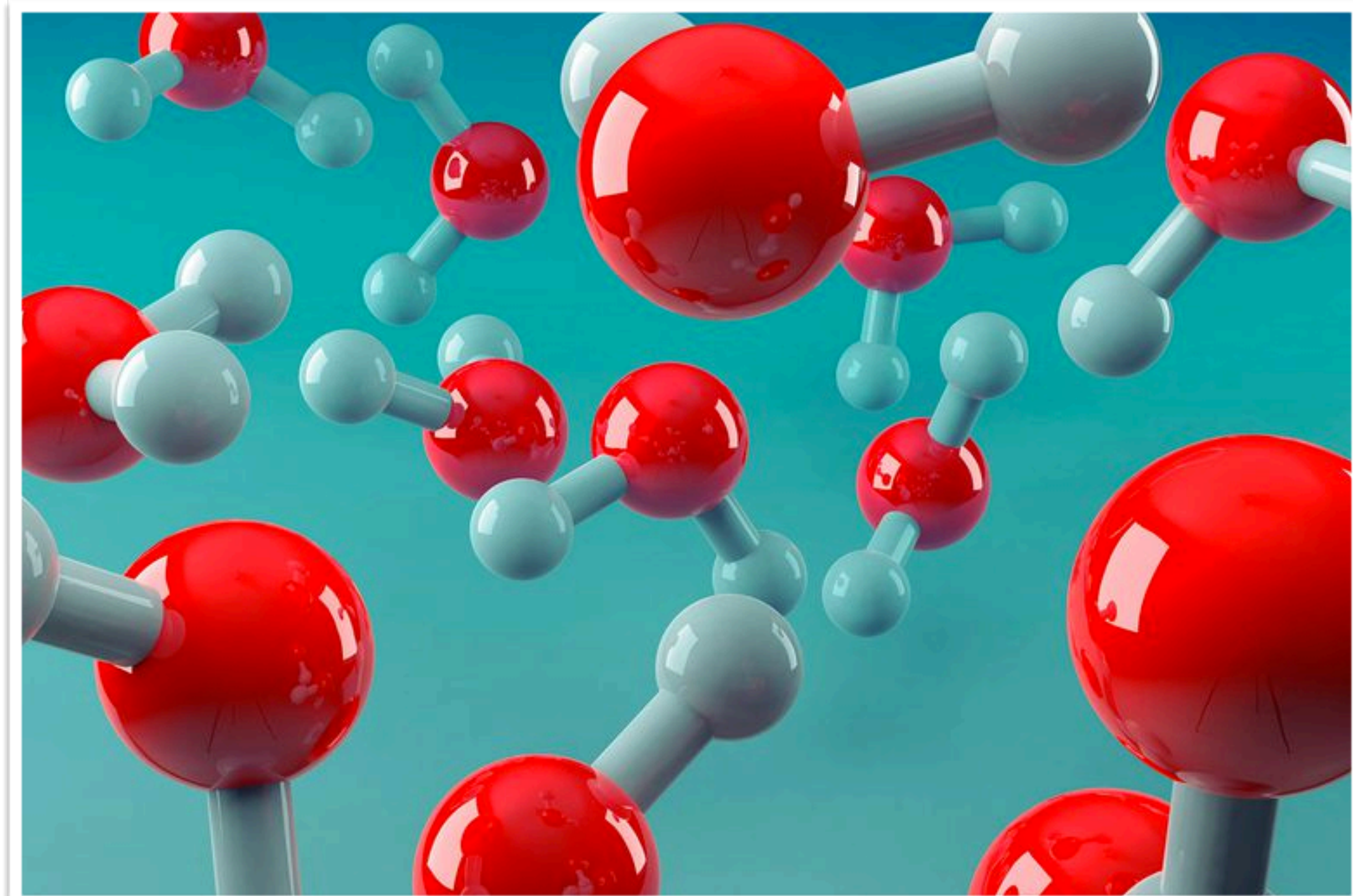
Getting started

- 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

Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.732	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [298]	117 Ts Tennessine unknown	118 Og Oganesson unknown

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Semimetal
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

©2016
The Periodic Table
of the Elements

The Atom

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

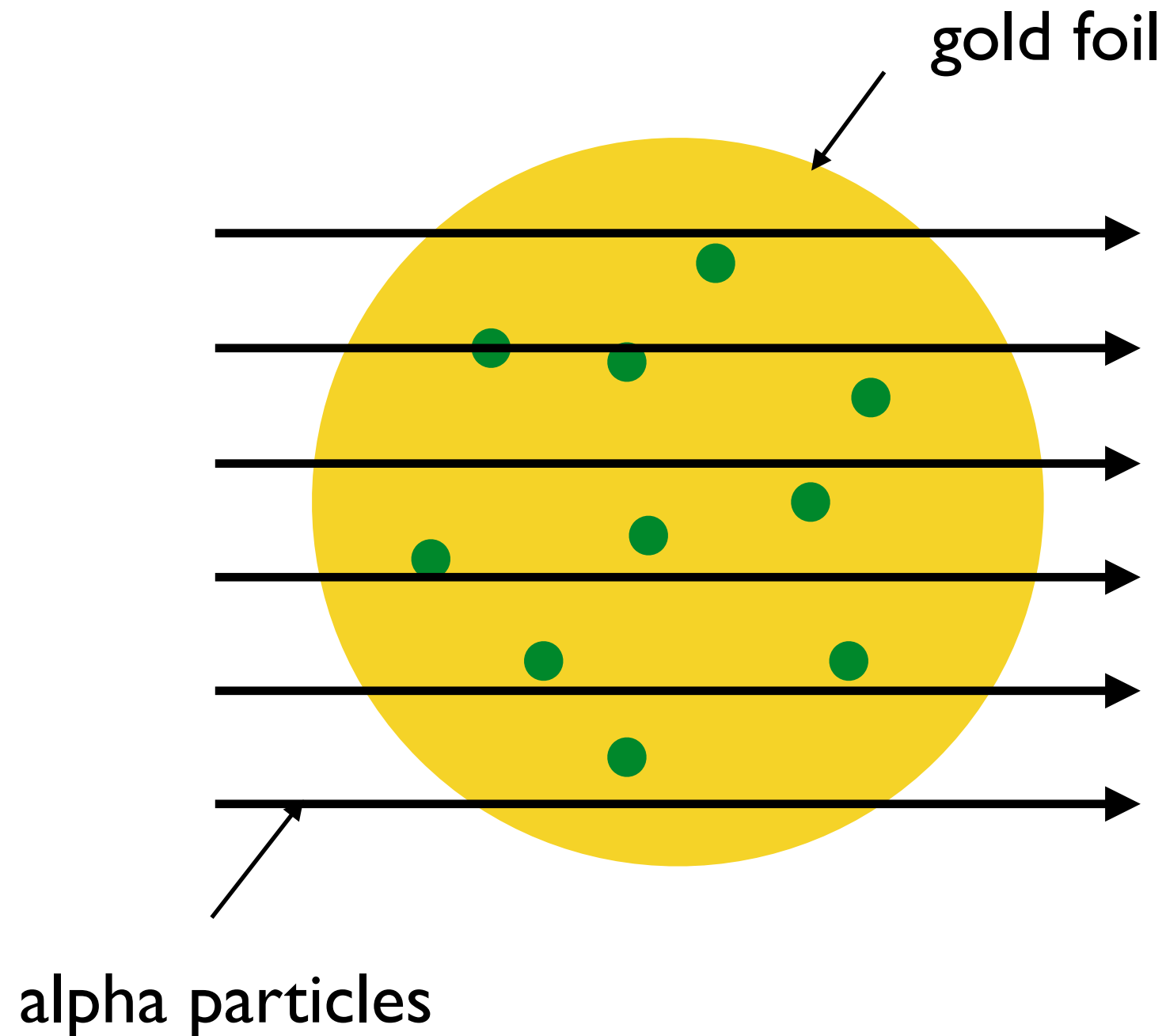


- But is the atom truly fundamental ?
 - experiment !



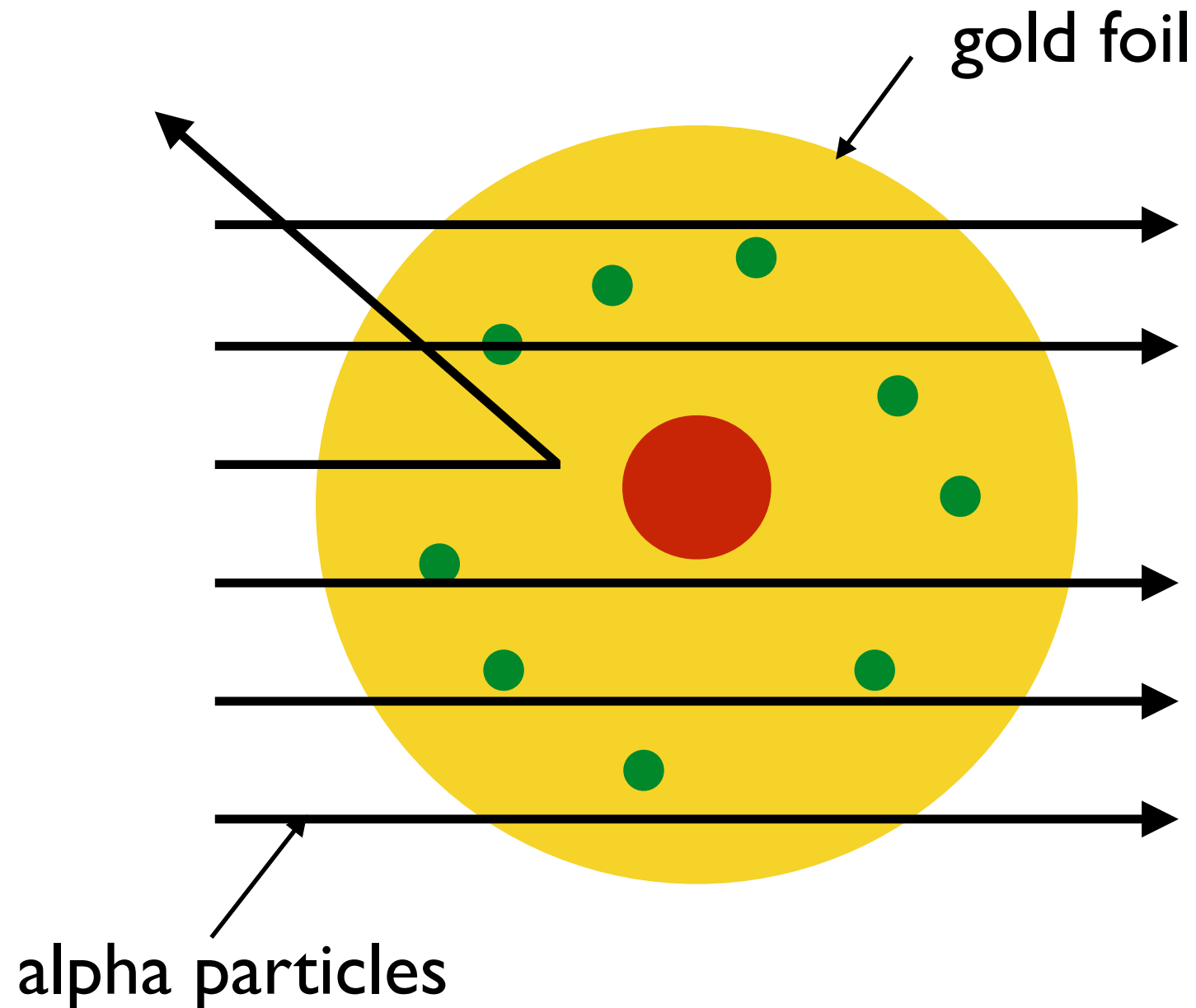
Geiger-Marsden Experiment (1909)

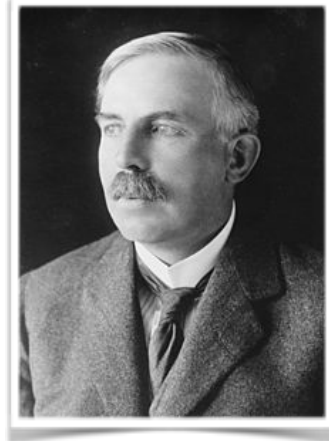
- Theory: atom was filled with diffuse charge
- Expectation: Alpha particles would pass through the foil



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 ...

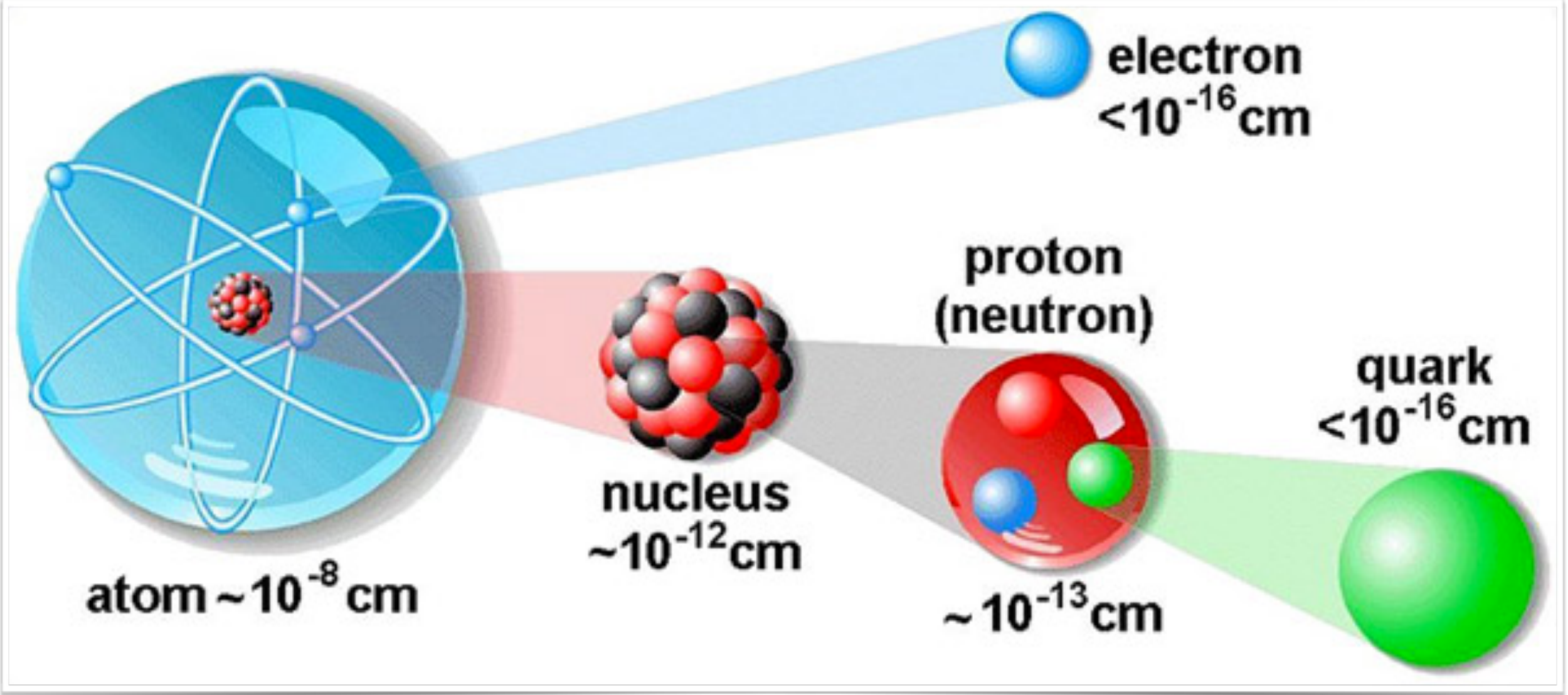




“It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

Ernest Rutherford

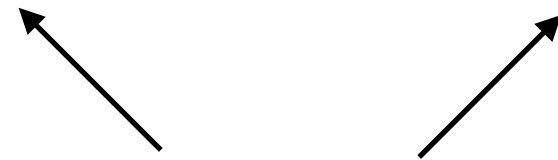
Current answer: quarks!



Reminder: Tiny Numbers

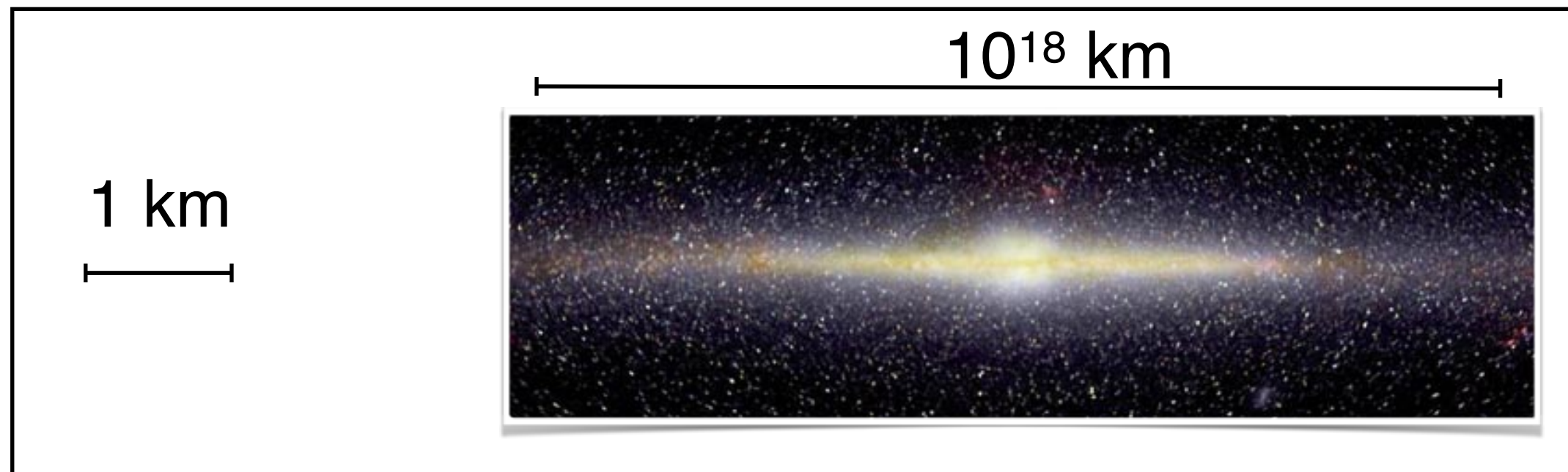
- 10^{-22} m is quick to write, but it's a deceptively tiny number

- 0.000000000000000000000000000000000001 m



22 zeros

Tiny Numbers



The Standard Model

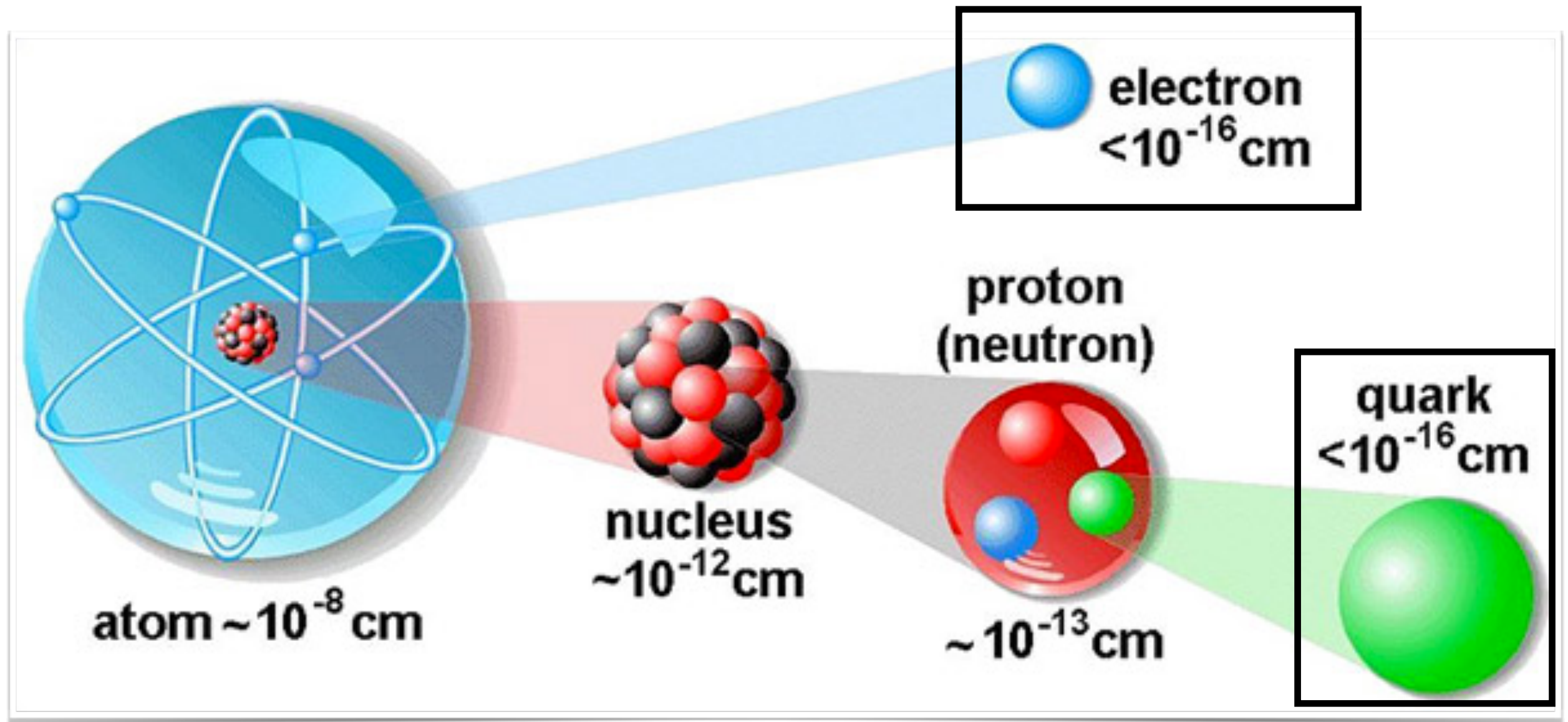
- Our current fundamental* theory
- **Matter:** the fundamental constituents of the universe
 - the elementary particles
- **Force:** the fundamental forces of nature
 - interactions between elementary particles



*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



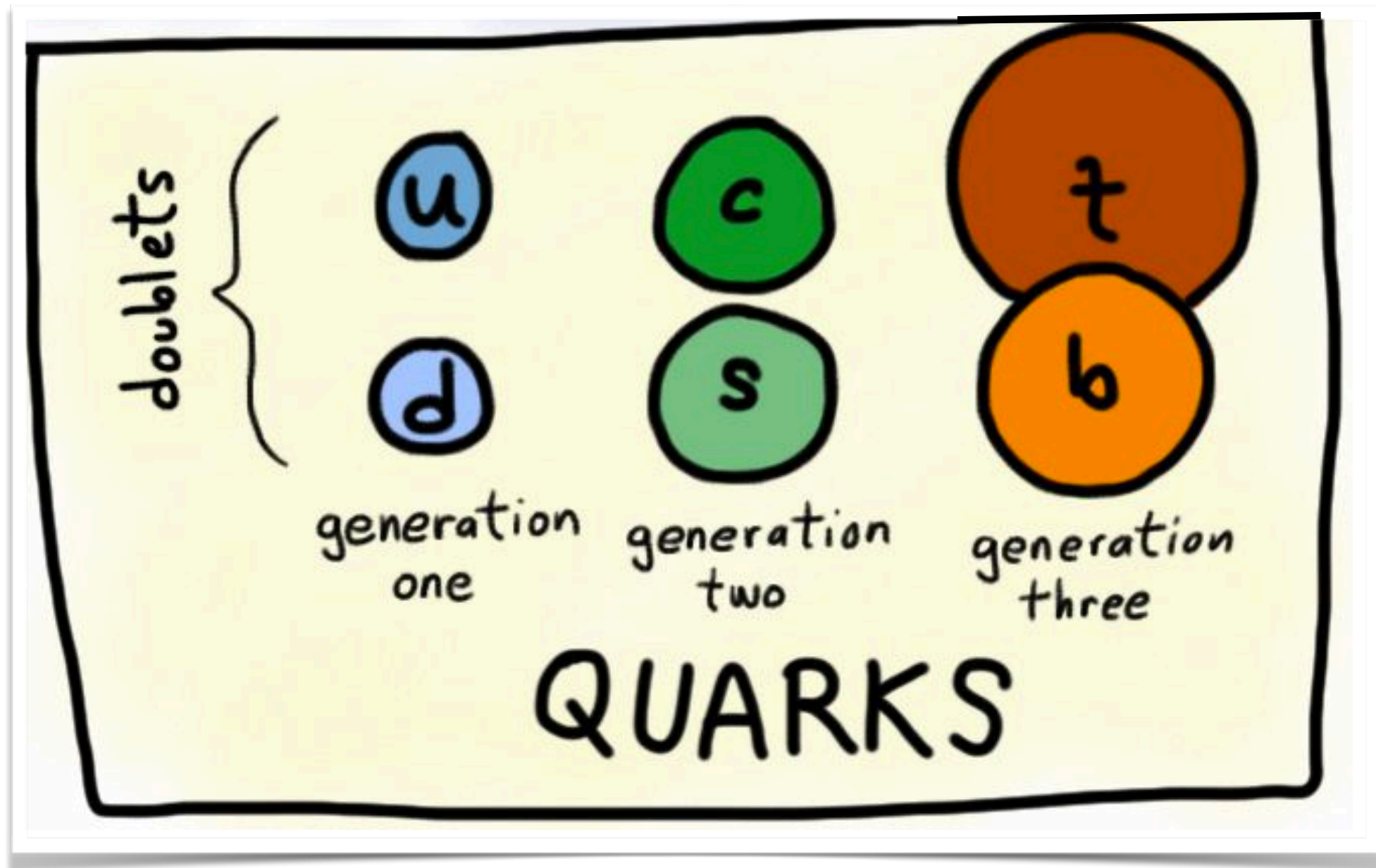
Image courtesy of Y. Beletsky

Something weird ... clones !

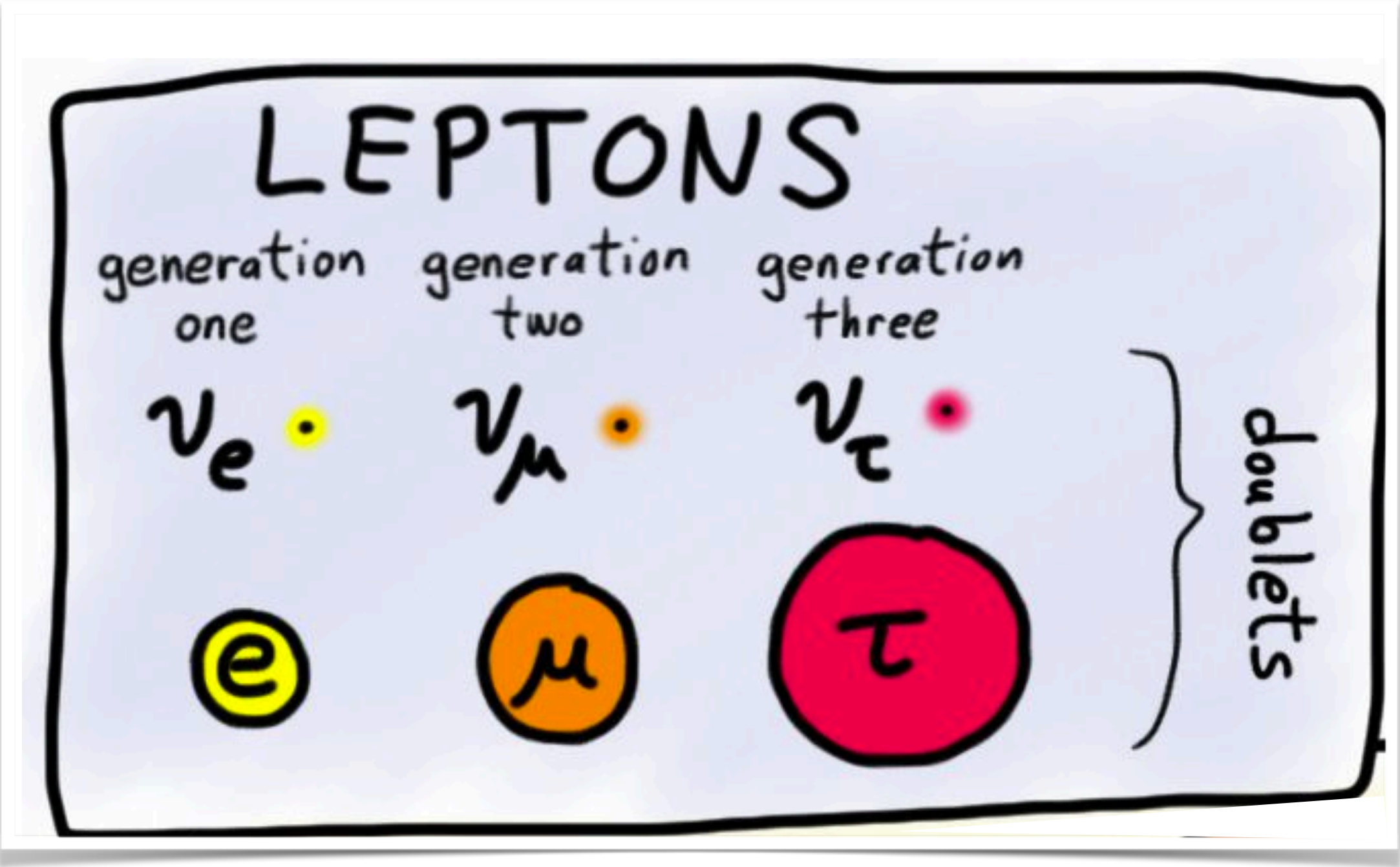


Credit: Courtesy Daisuke Takakura

Quark Families



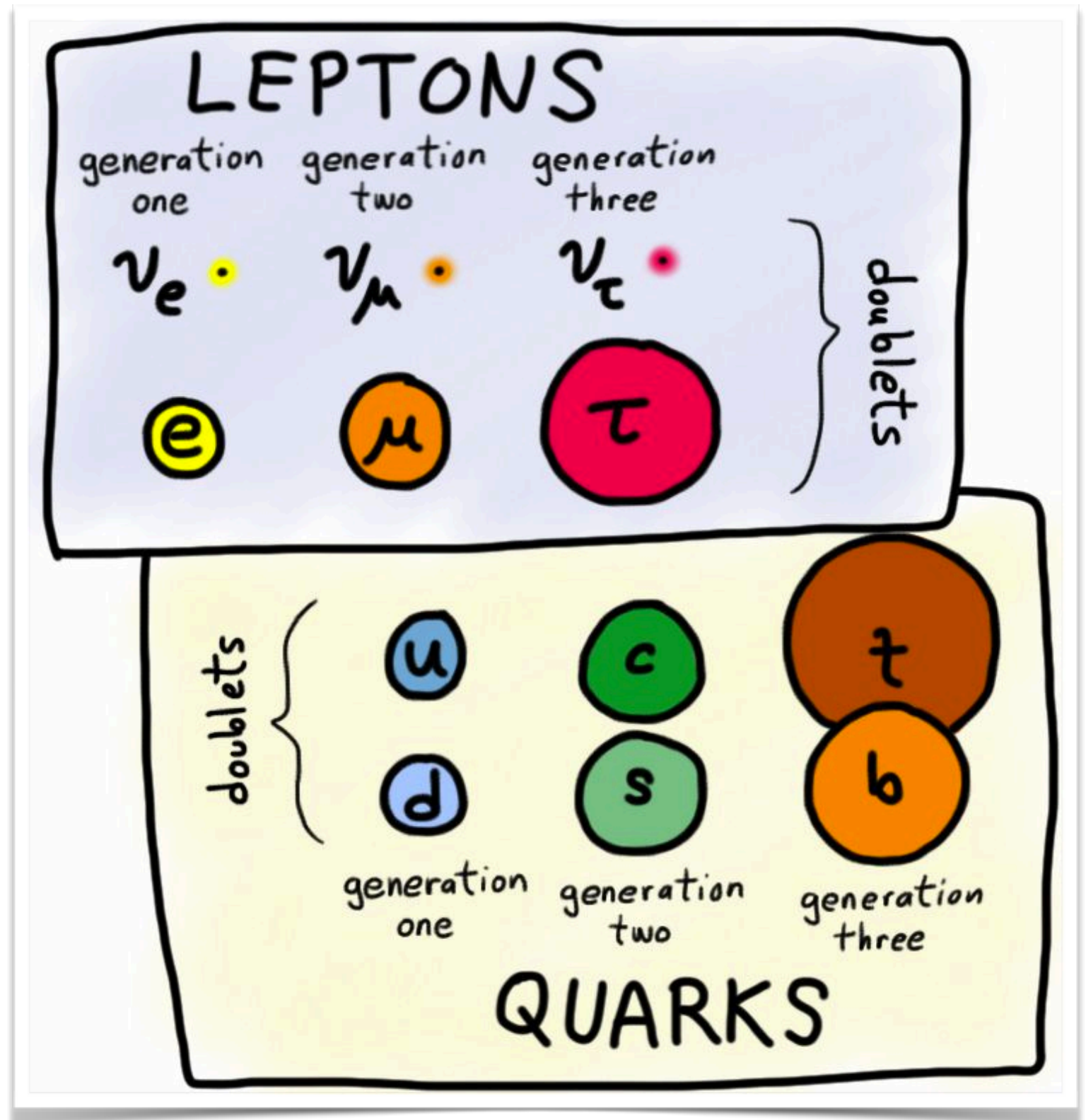
Lepton families



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

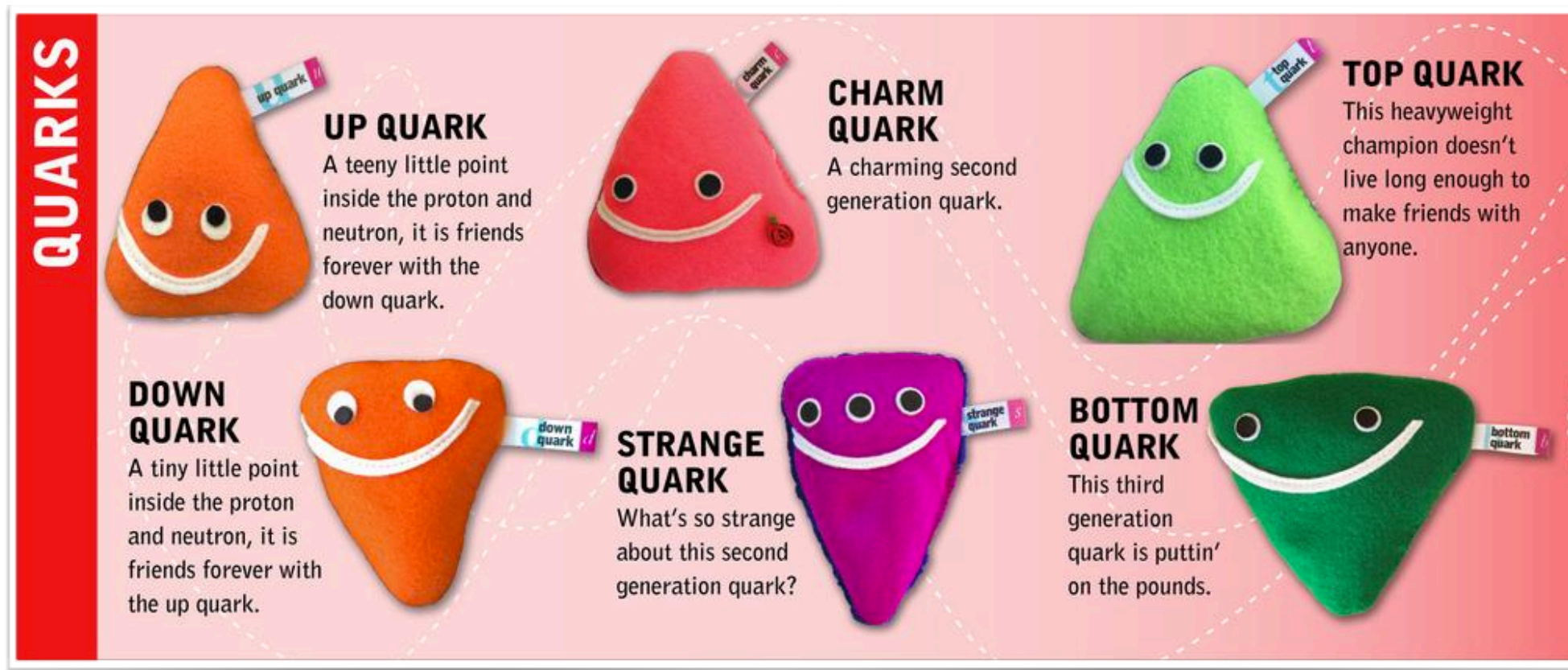
Why are there six quarks and leptons ?

- 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**
- **Strangely** 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?

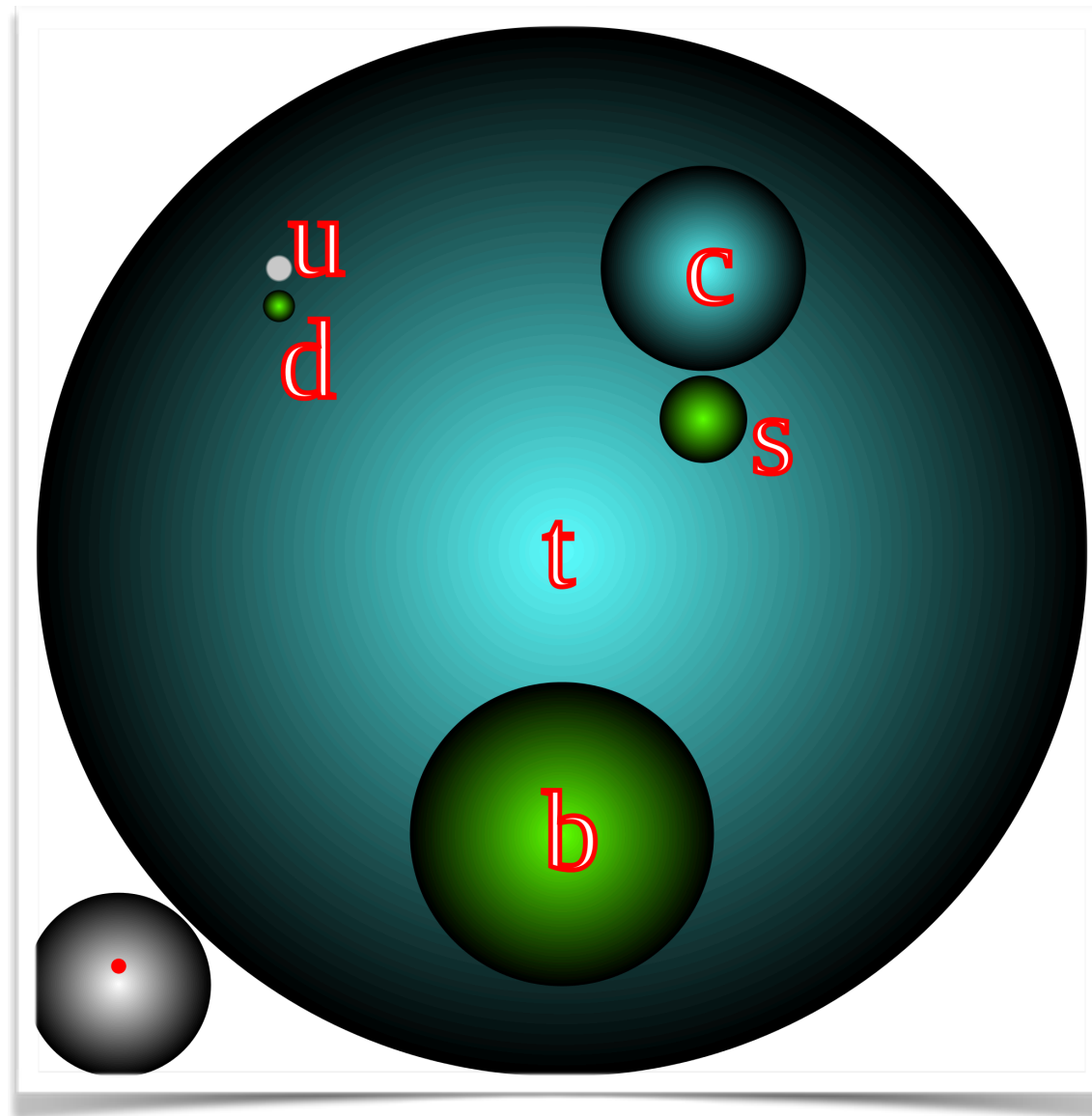
How big is a quark?

- 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

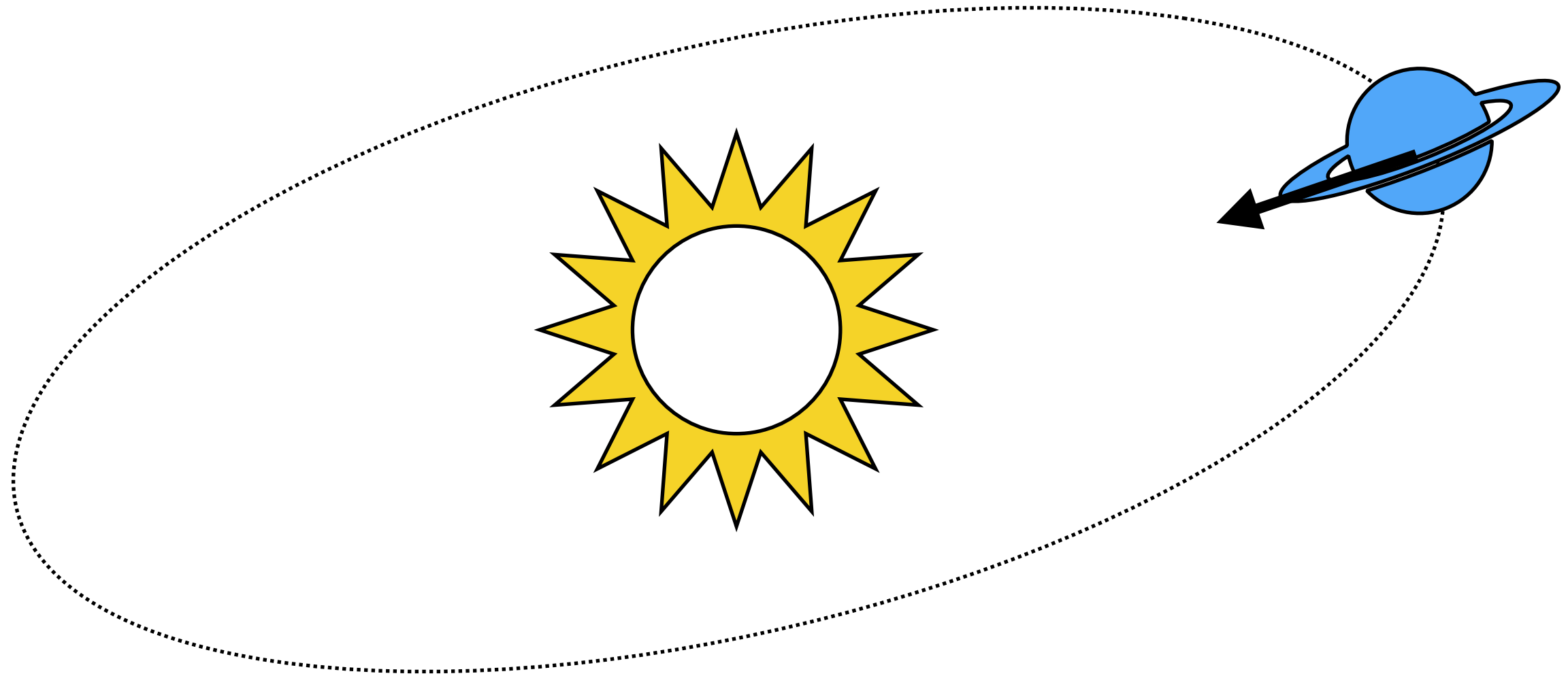
The **top** quark is 60000 times heavier than the **up** quark
Why? Again, we don't know yet



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

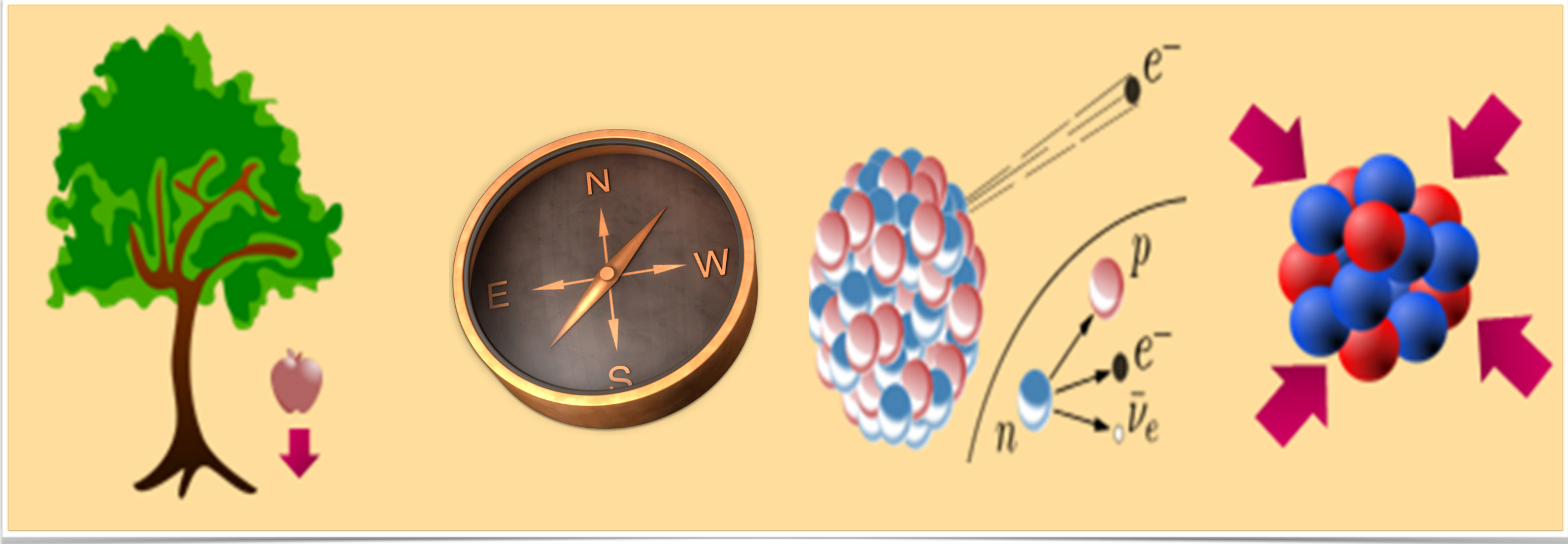
Four Fundamental Forces

Gravitation

Electromagnetism

Weak

Strong



graviton

photon

W/Z boson

gluon

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

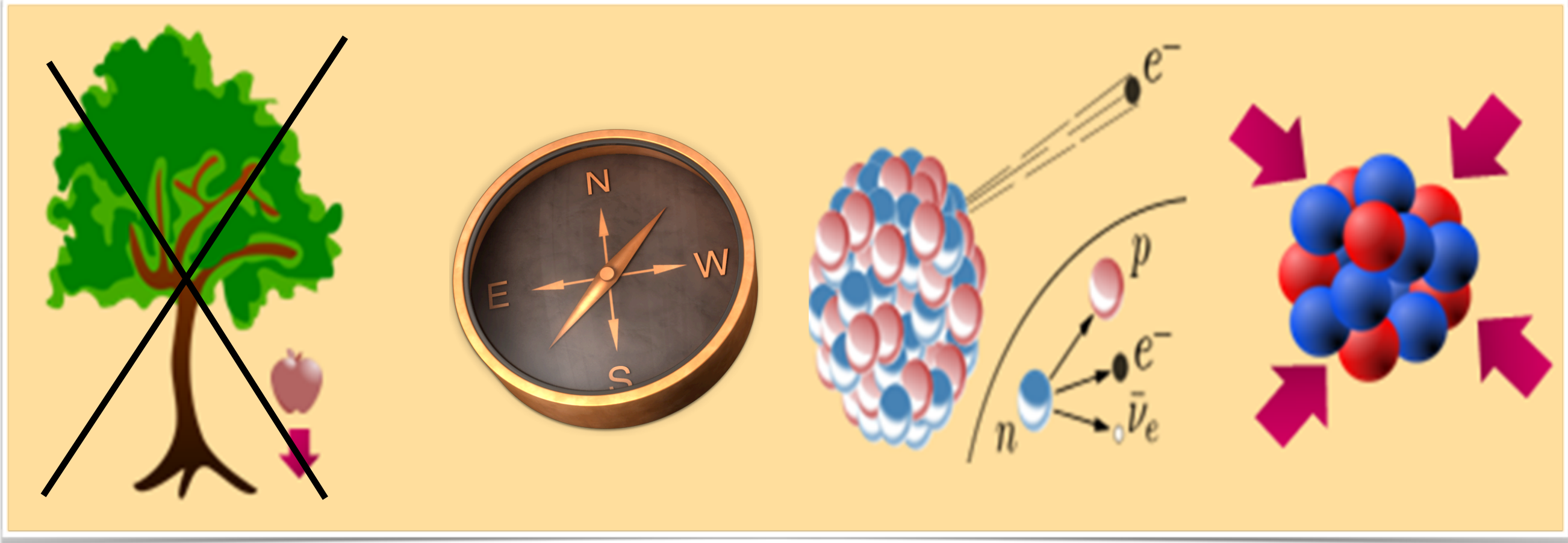
Four Fundamental Forces

Gravitation

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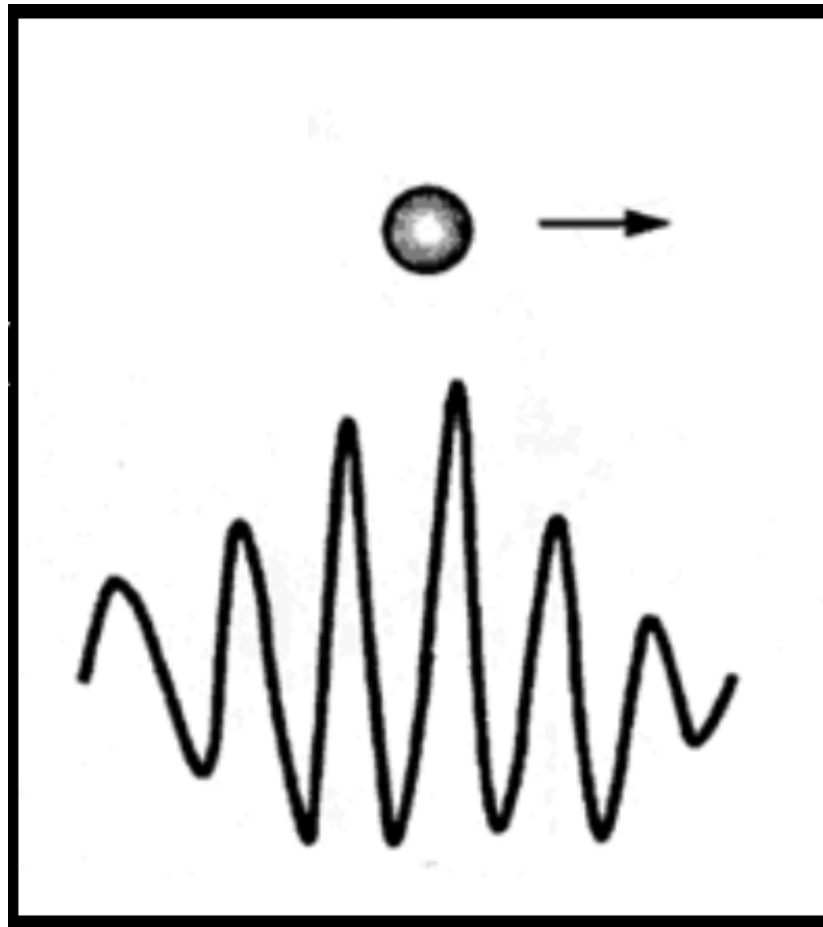
W/Z boson

gluon

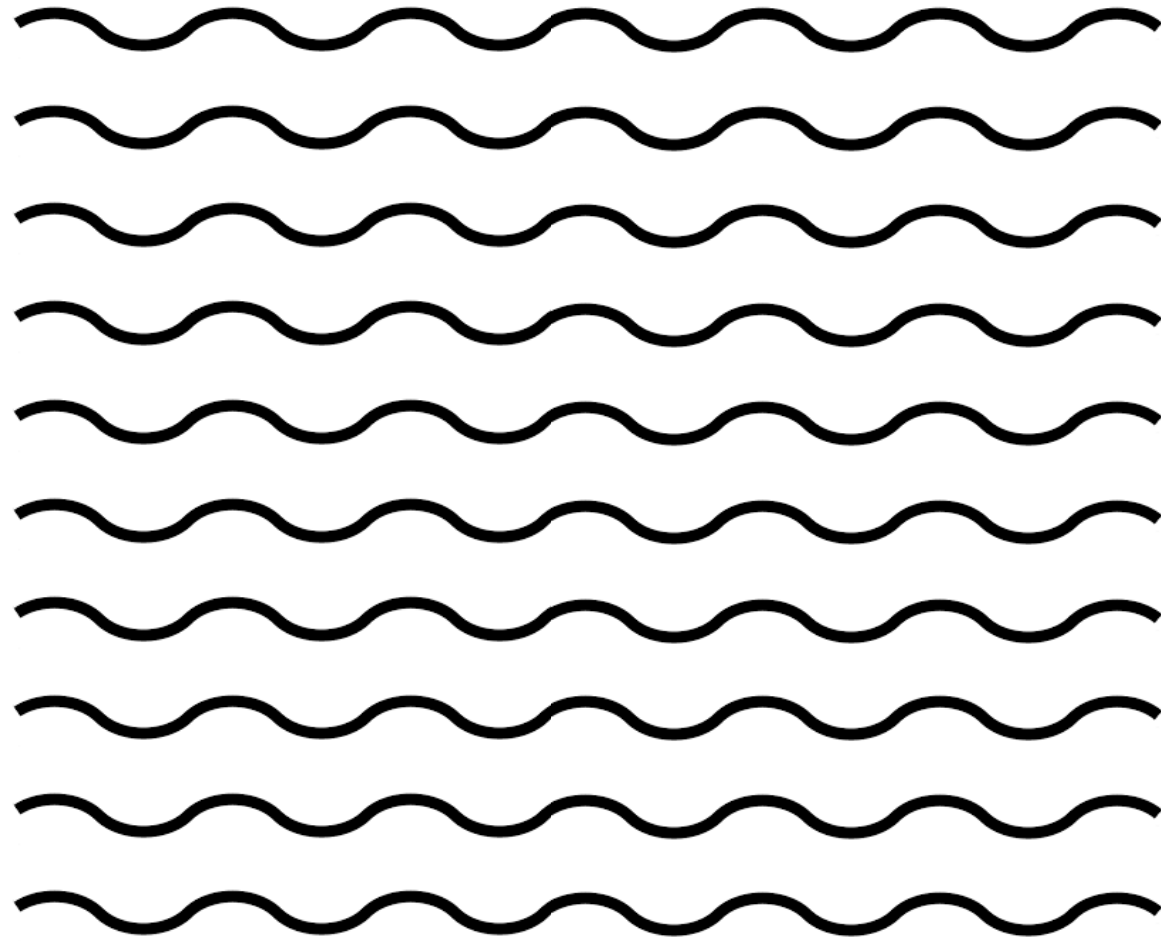
Credit: https://commons.wikimedia.org/wiki/File:FOUR_FUNDAMENTAL_FORCES.png

Wave-particle duality

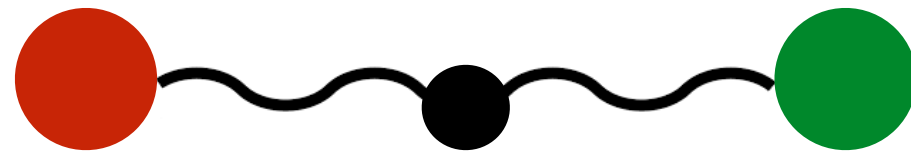
- Strange feature of quantum mechanics
- Simultaneously particle and a wave/field



Field

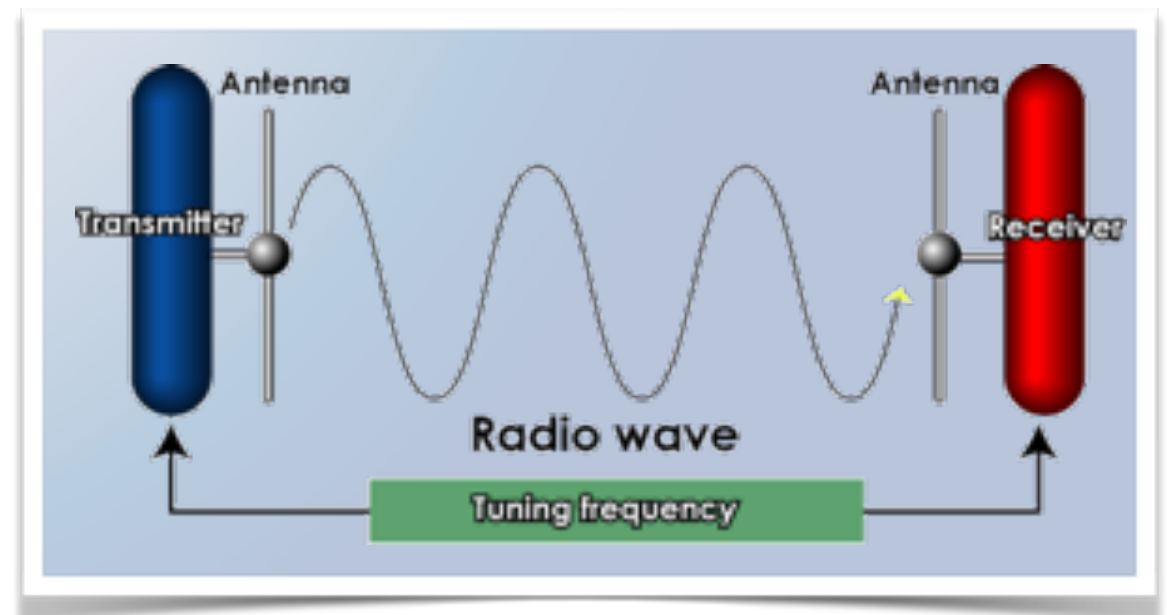
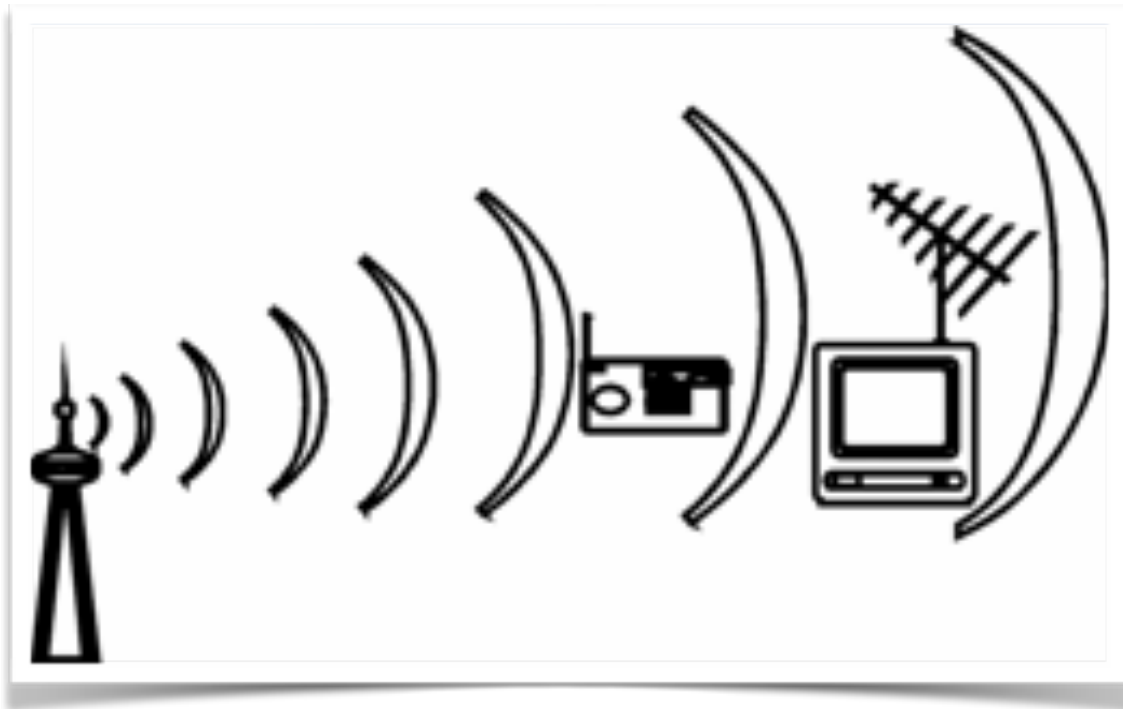


Particle



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



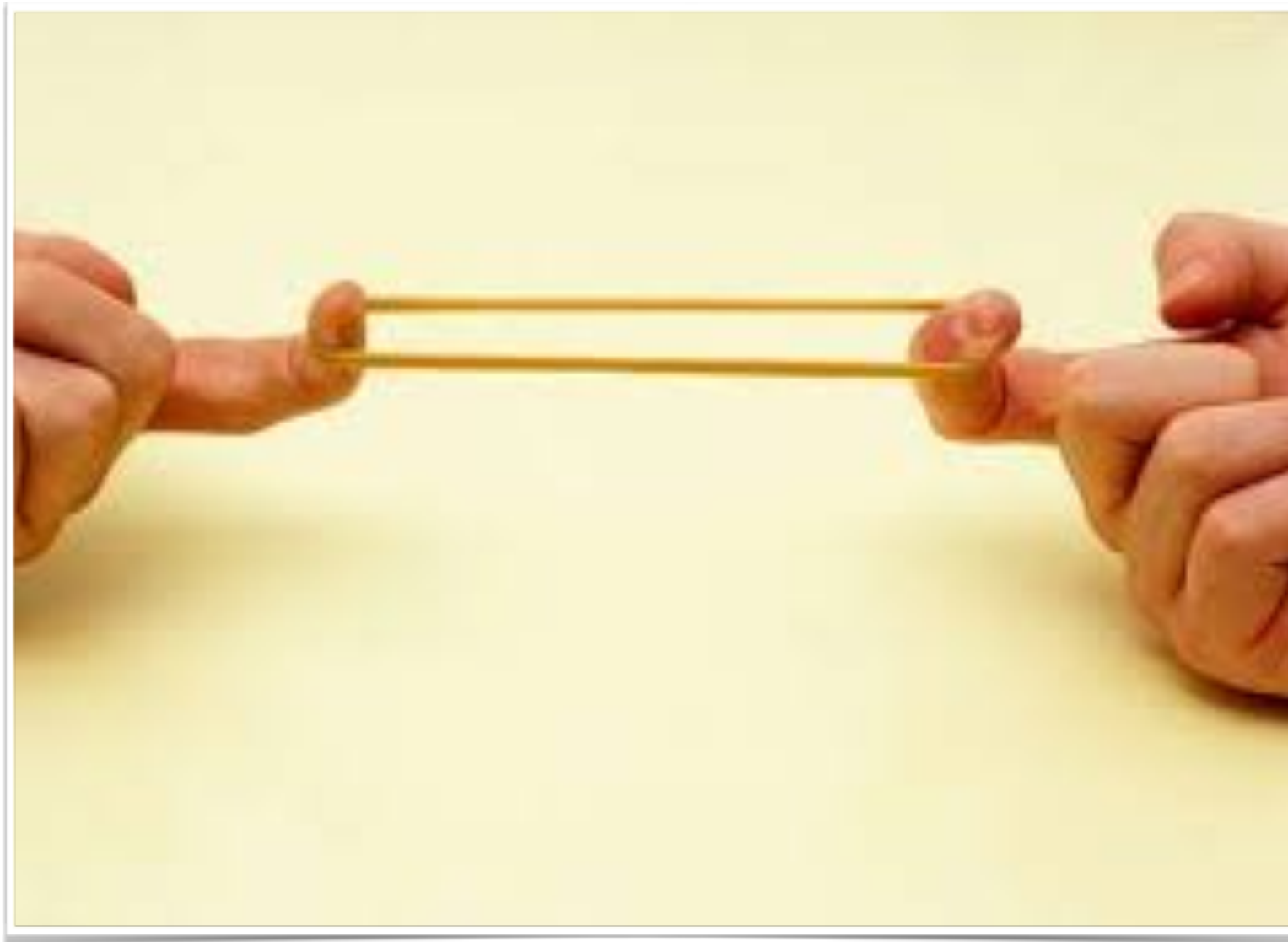
The Strong Force

- 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



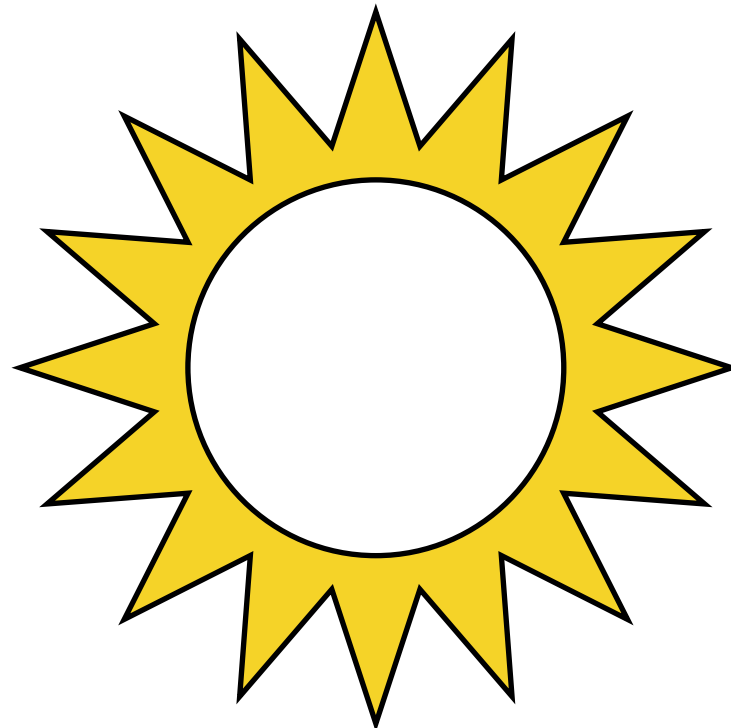
Peculiarities of the strong force

- 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

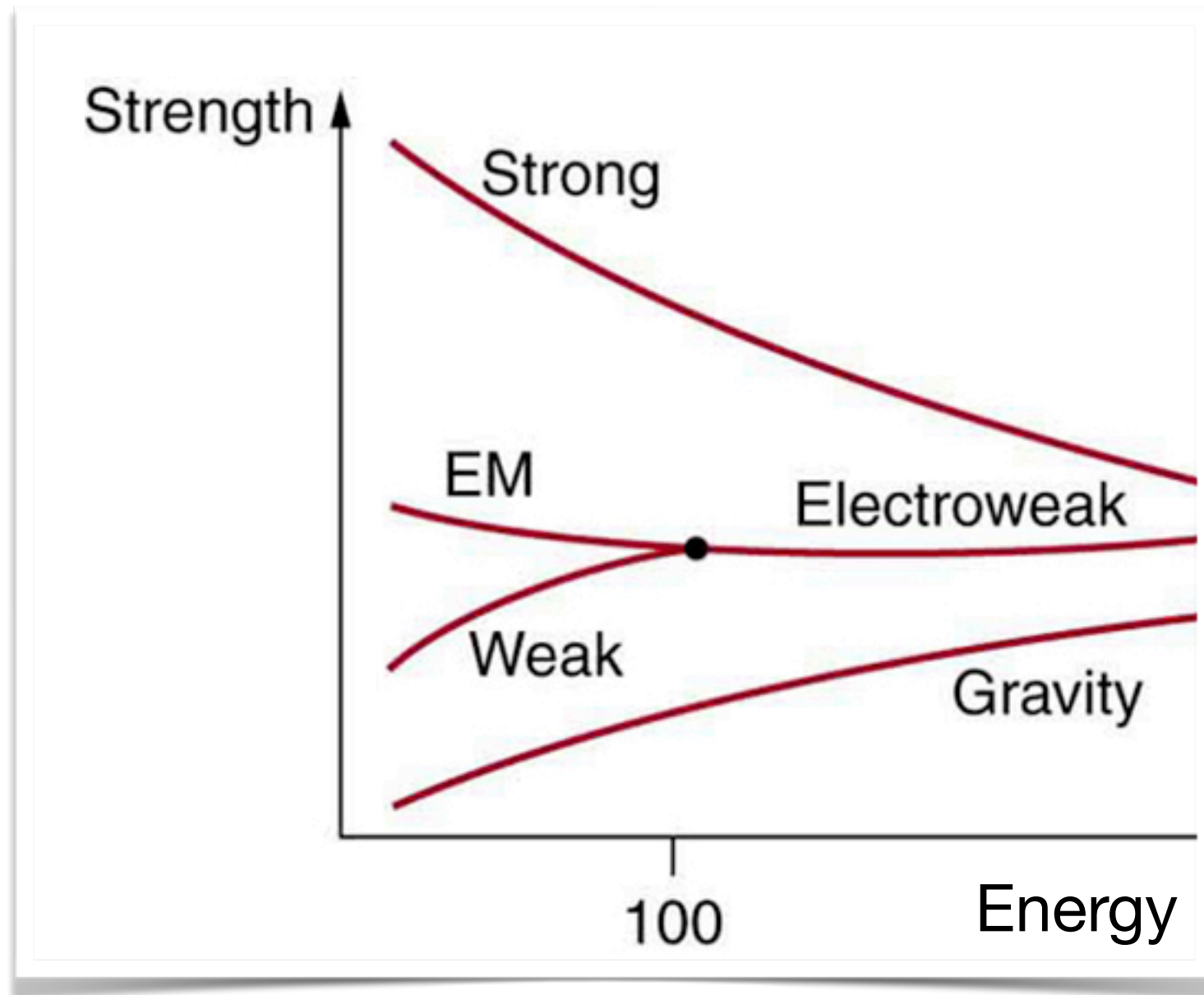


Relative strength of the forces

- 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

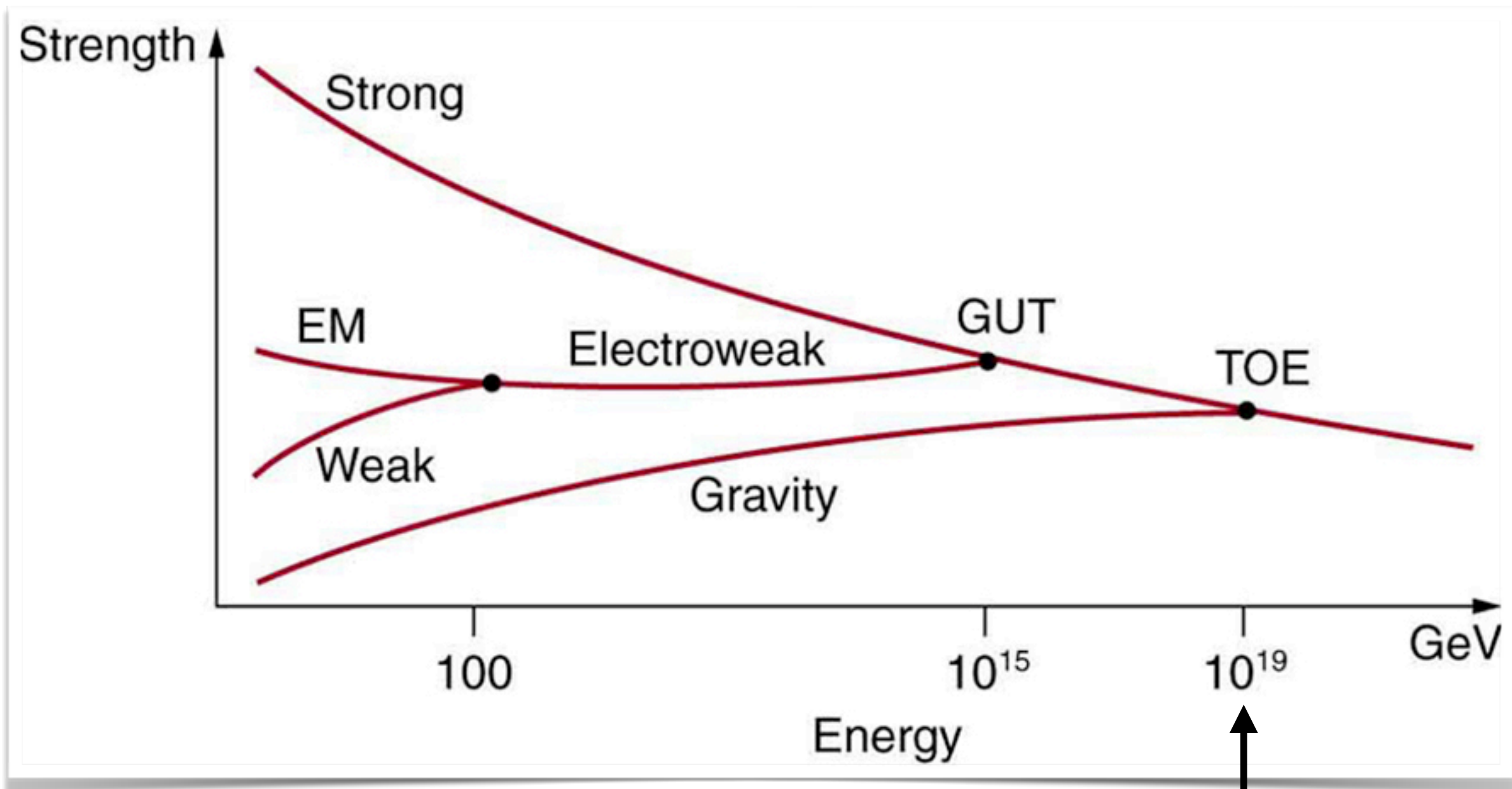
Unification

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

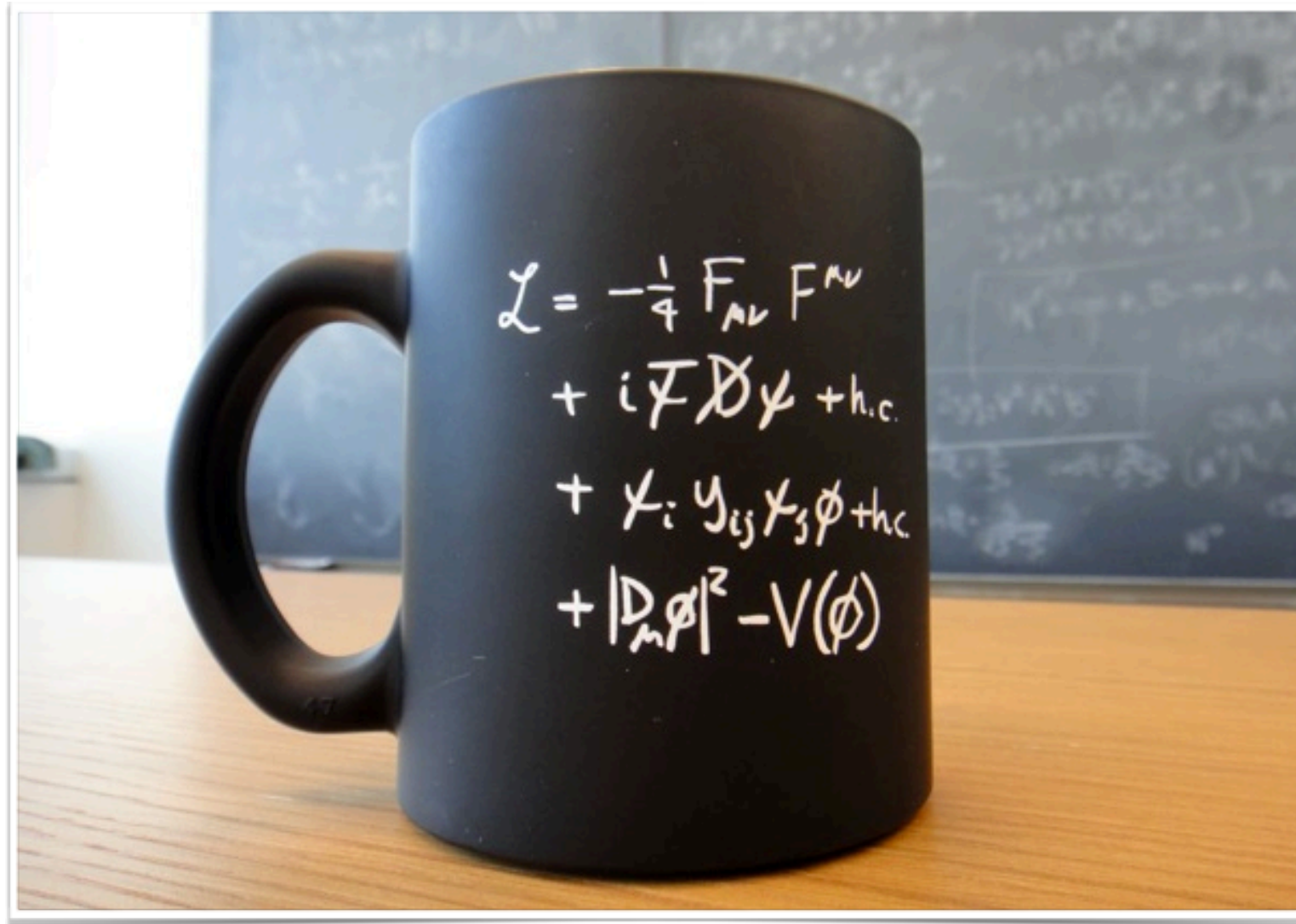


Quarks

Forces

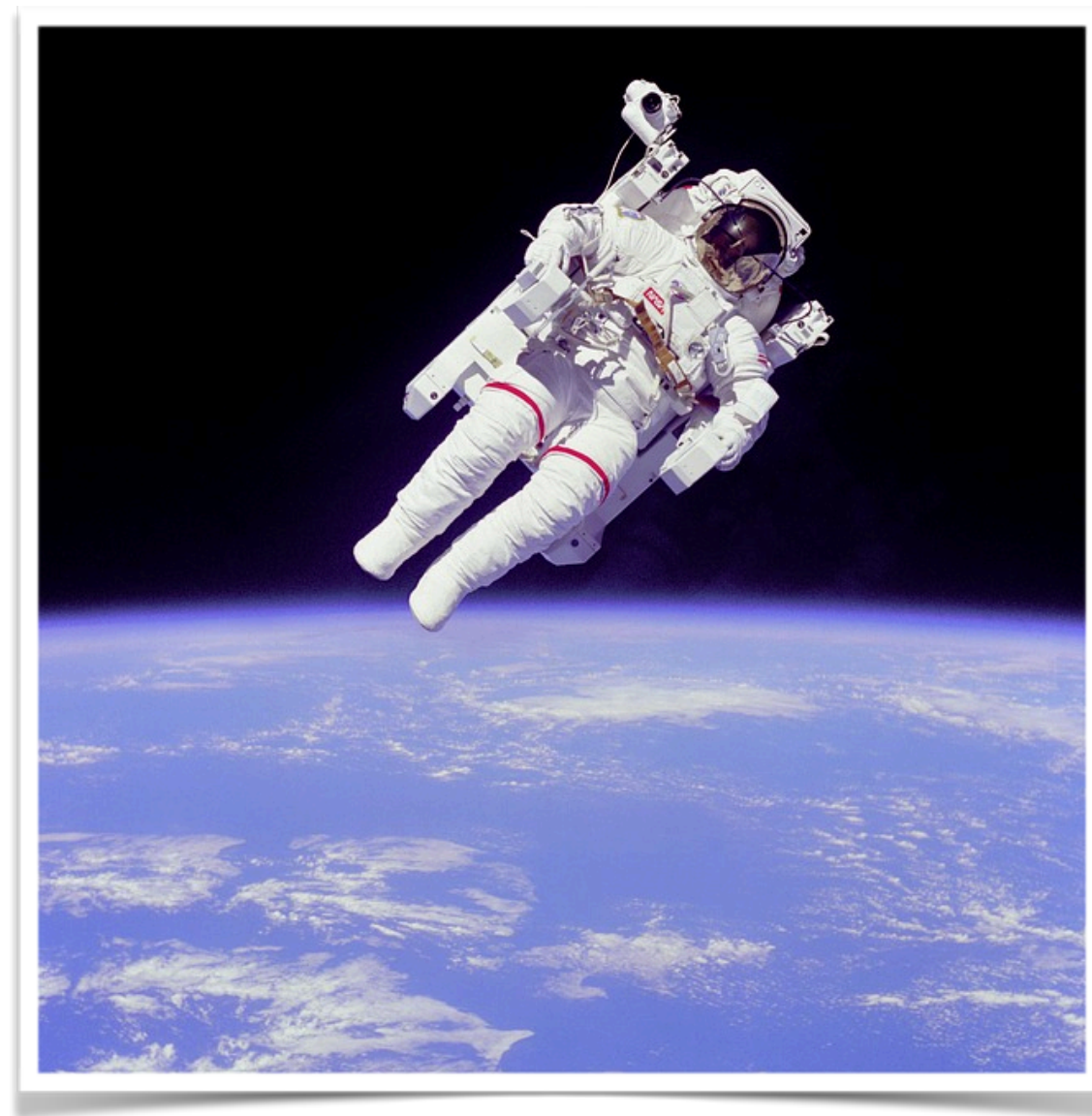
Leptons

The Standard Model

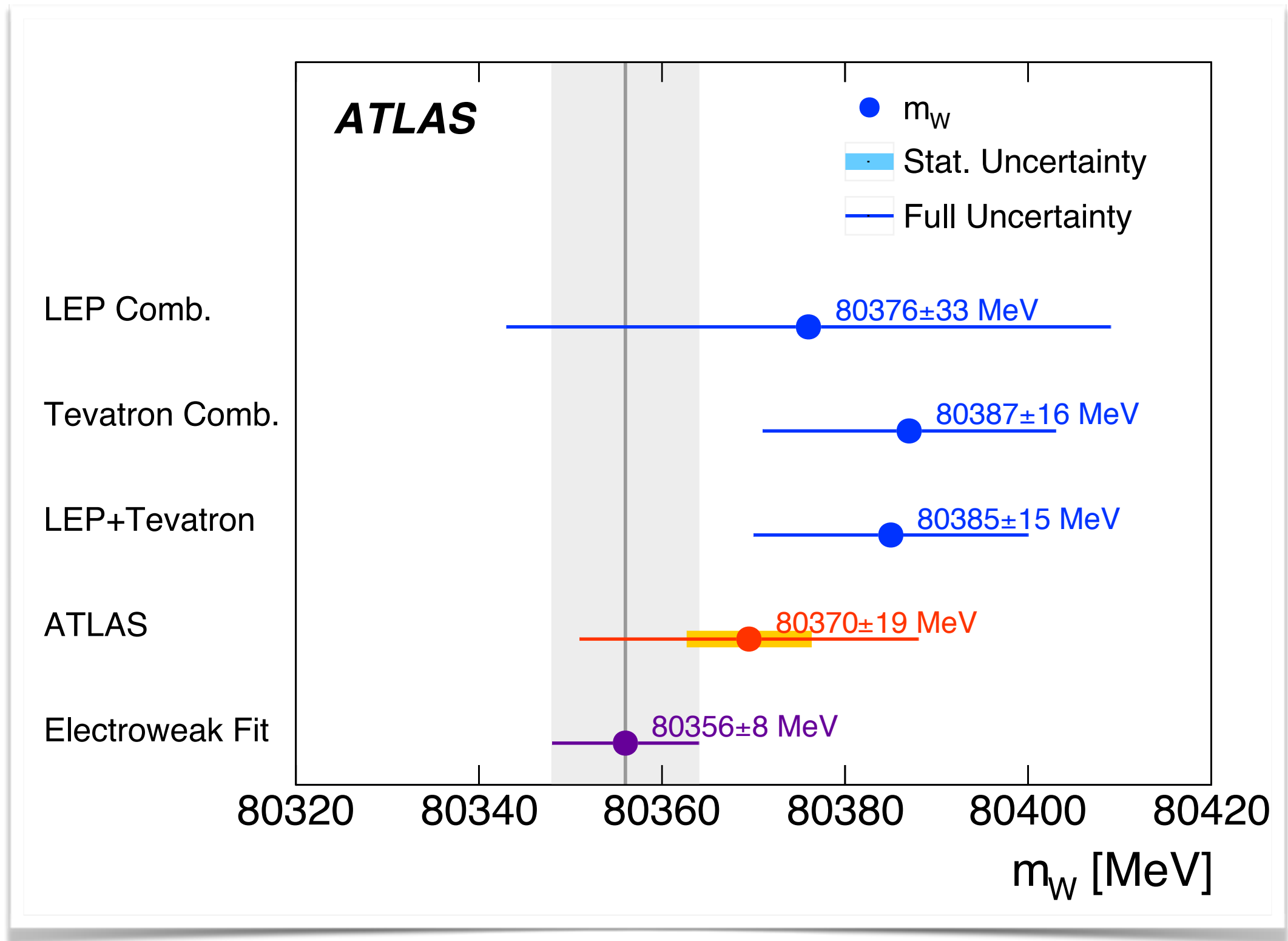


In mug equation form

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

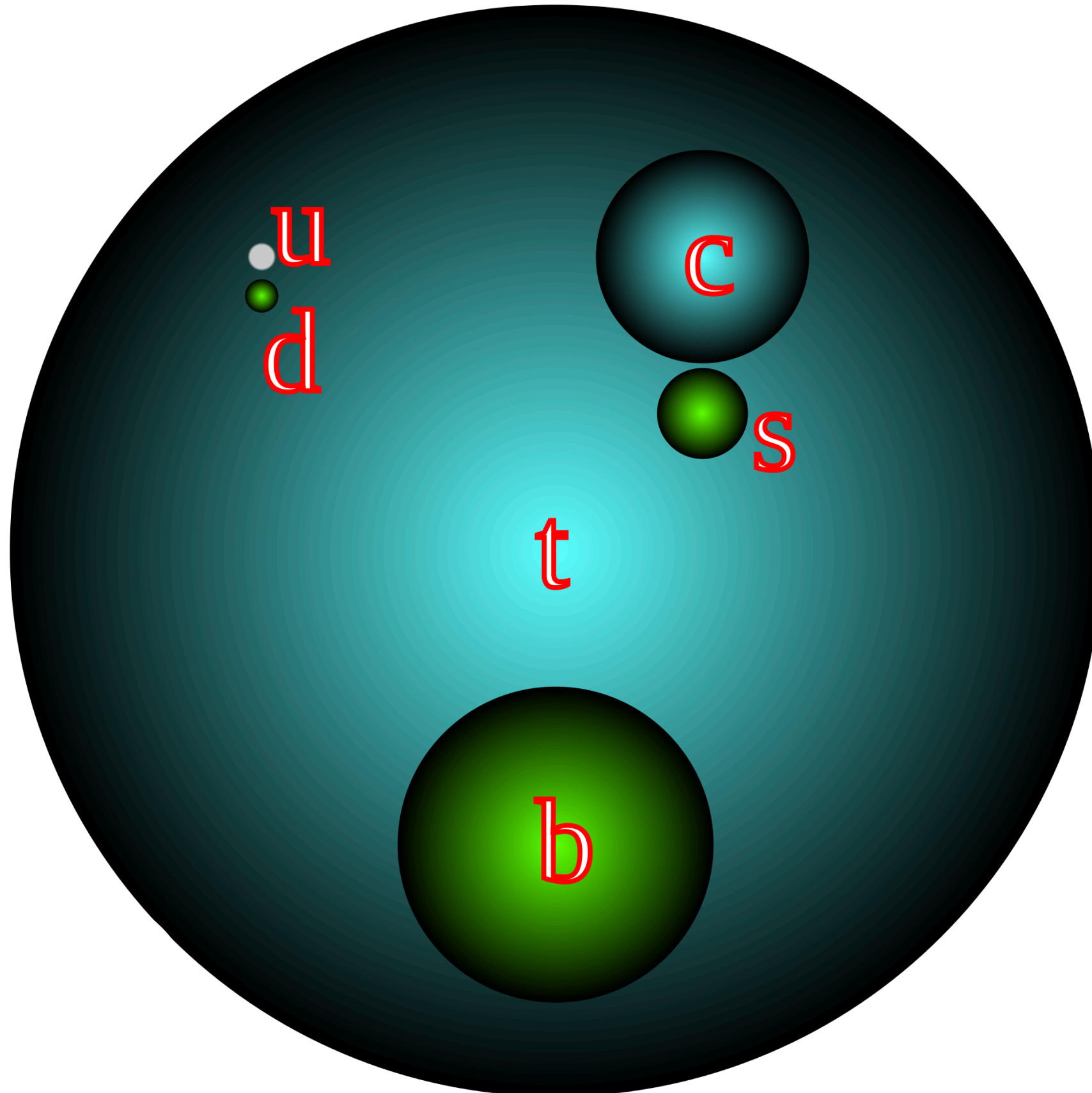


The W Boson has mass !

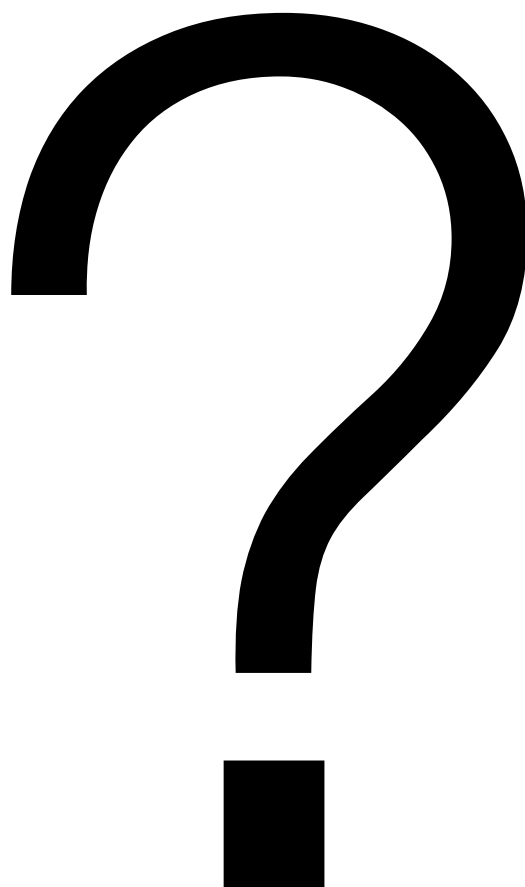


as does the Z boson

The quarks have (different) mass(es)!

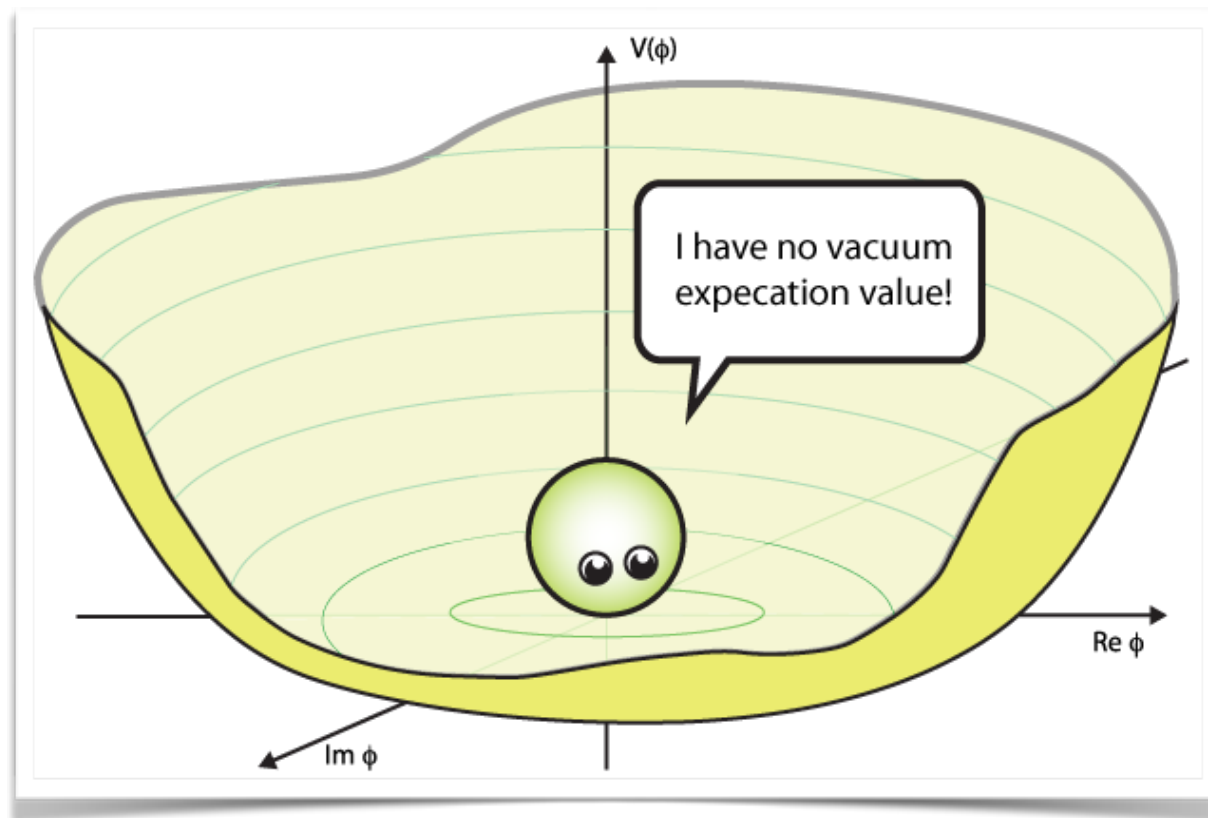


... as do the leptons

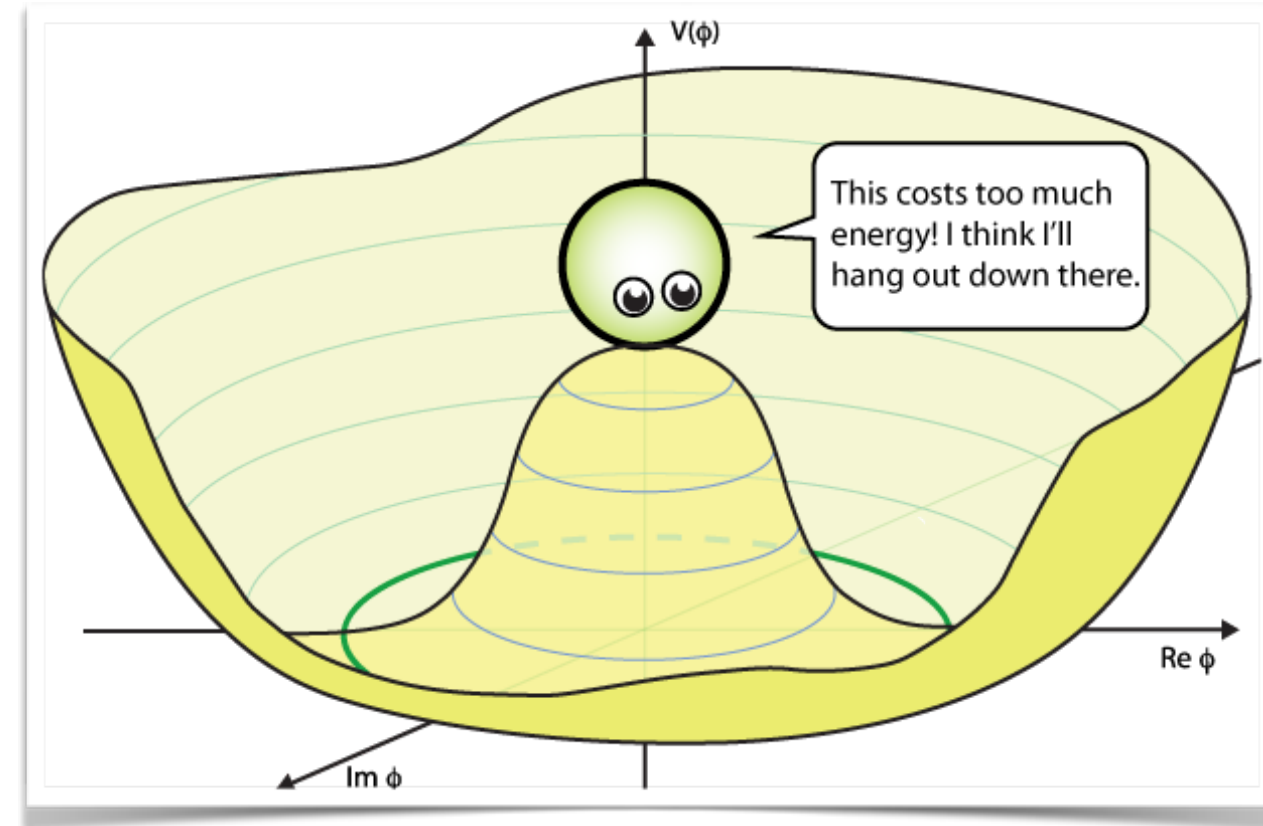


The Higgs Boson

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



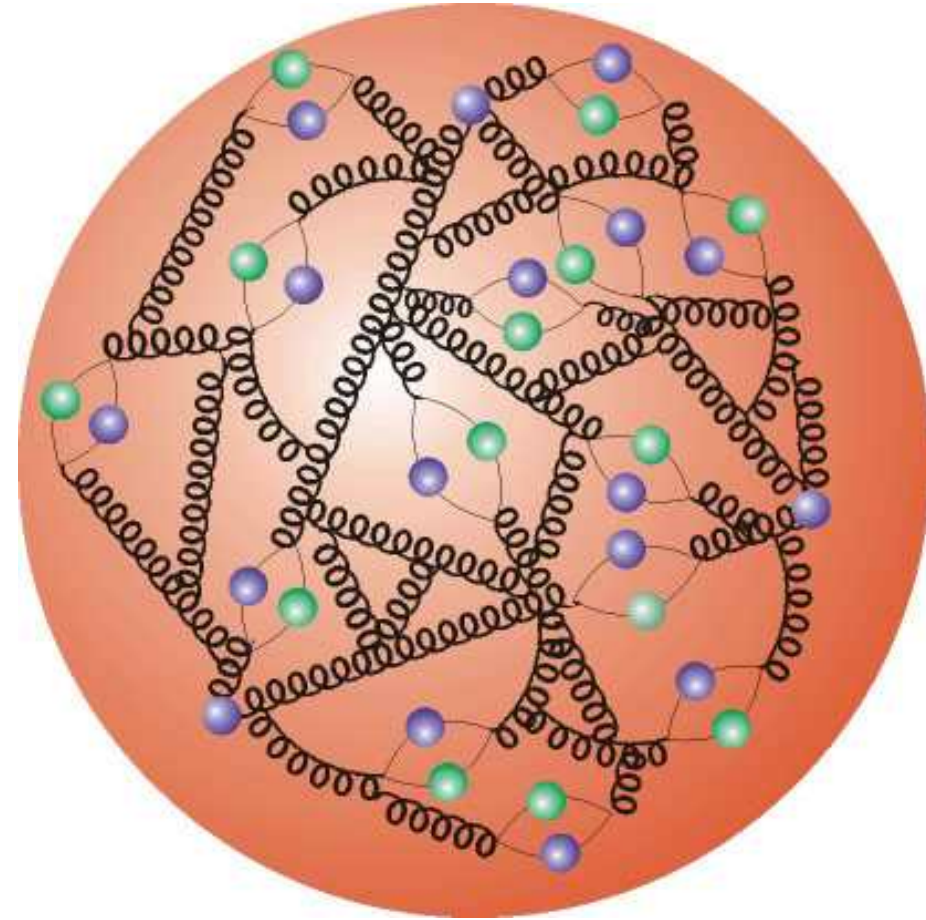
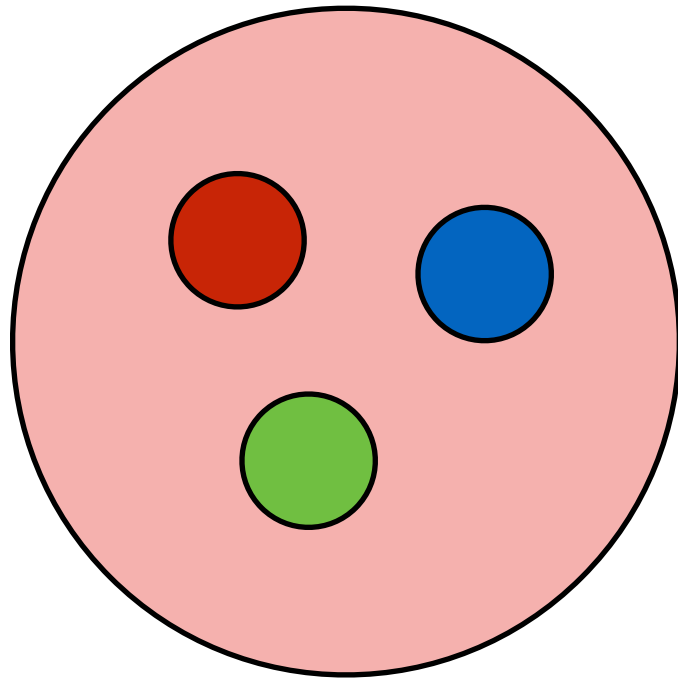
Analogy: Fisk Tank



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?

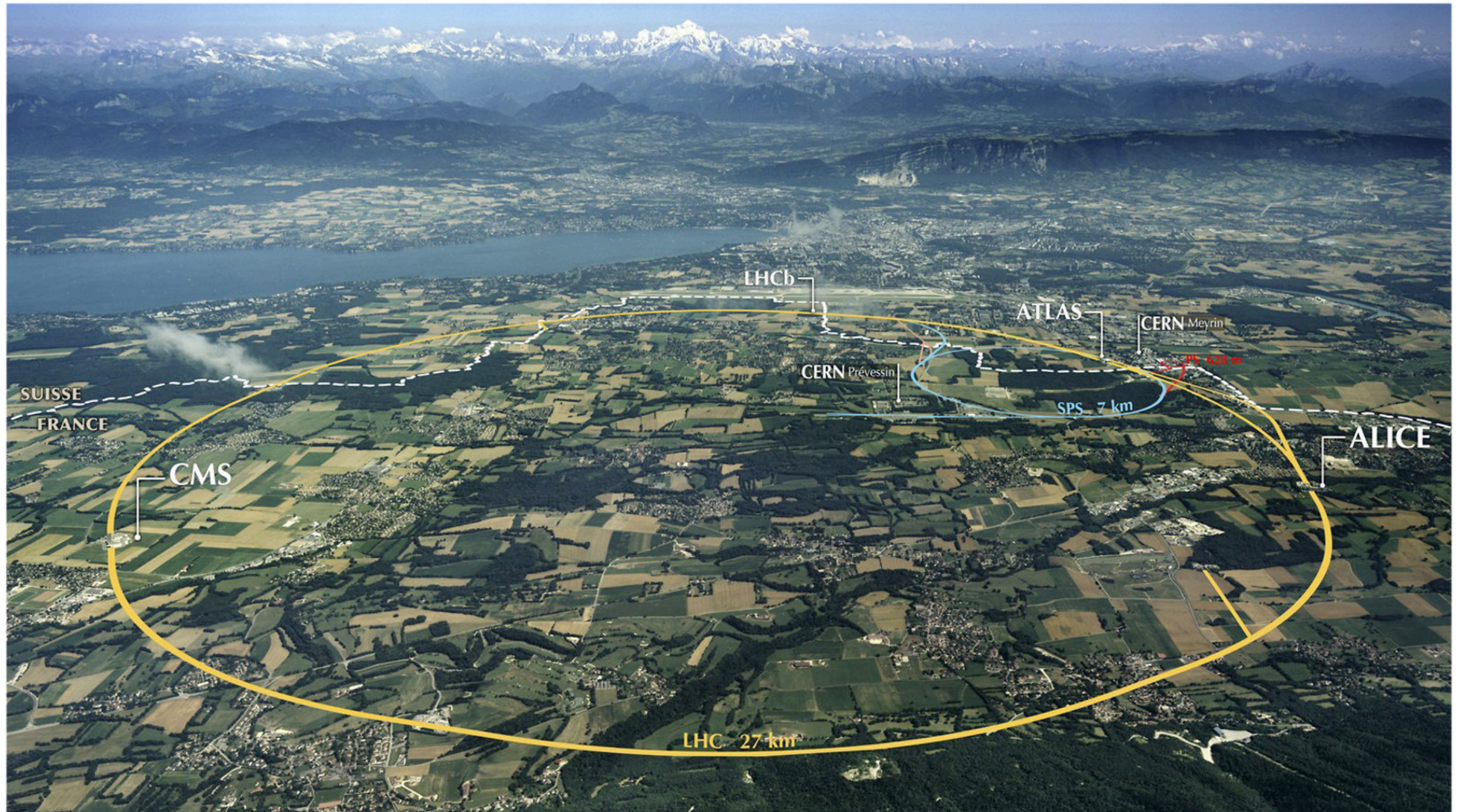
Microscopes



See tiny objects by magnifying the light they produce

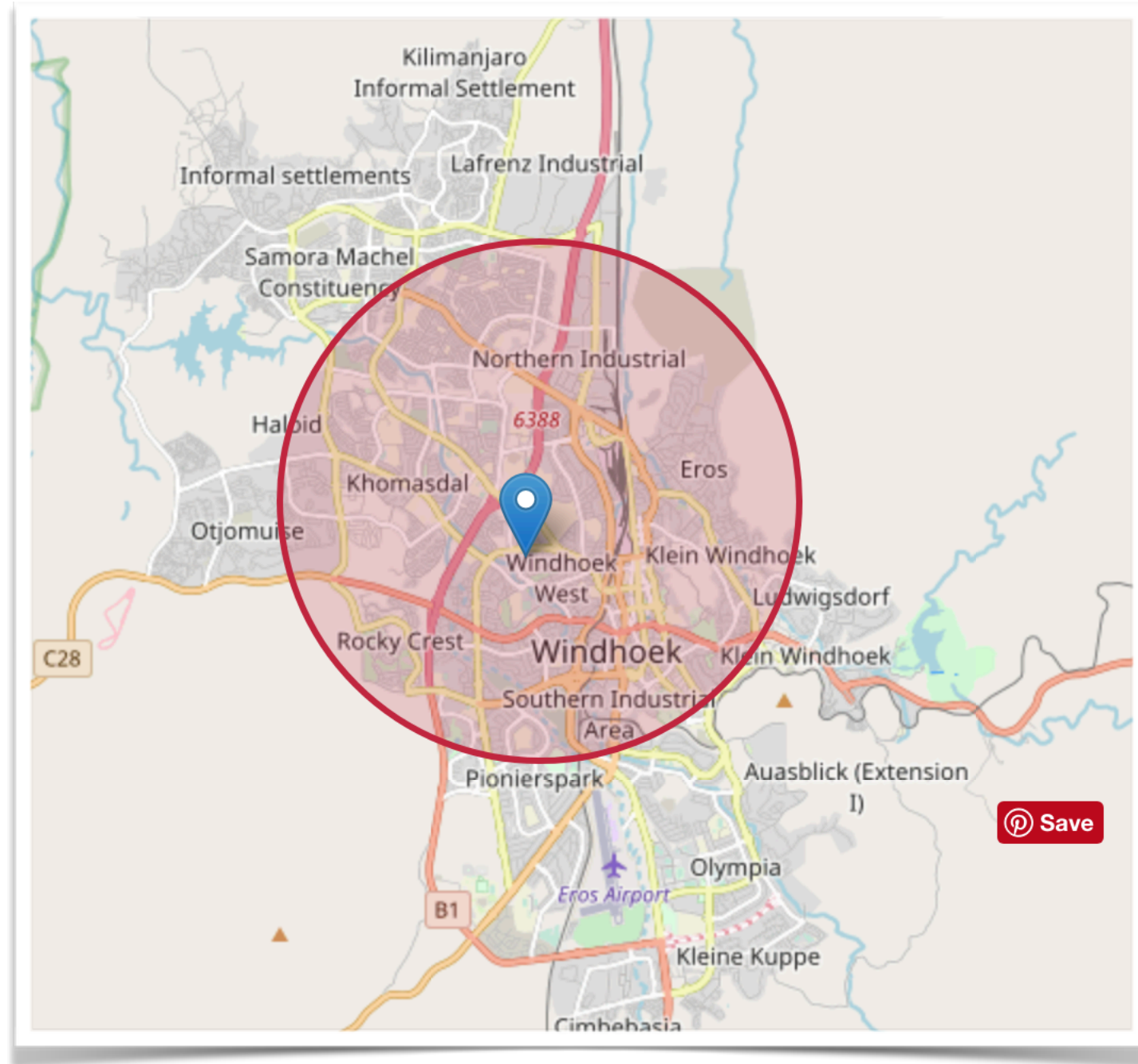
Our biggest microscope:

The Large Hadron Collider



How big is the LHC?

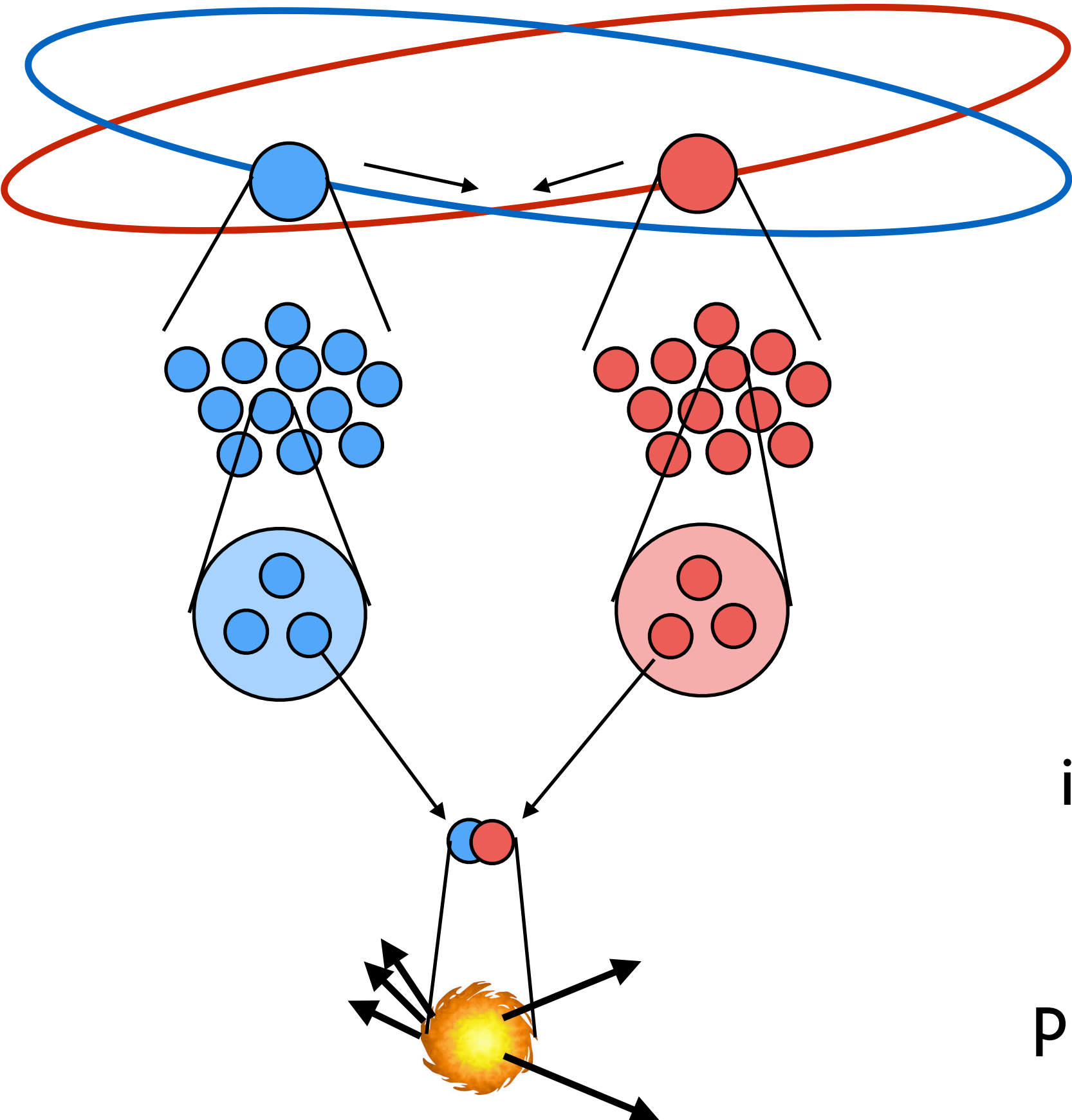
A 27 km long collider near Geneva, Switzerland



(Would cover most of Windhoek)

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

Collider basics



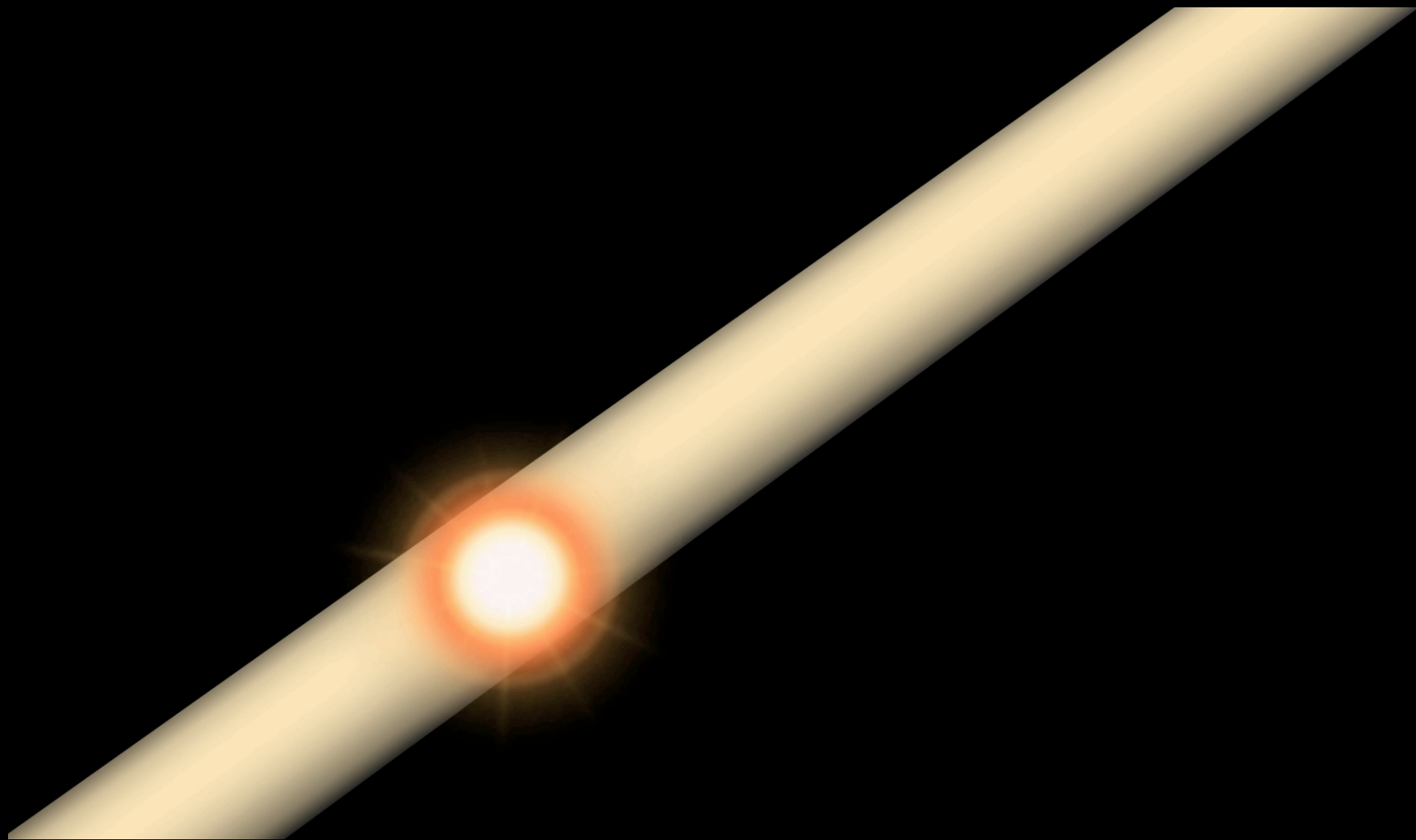
proton beams

bunches

colliding protons

interacting quarks
(or gluons)

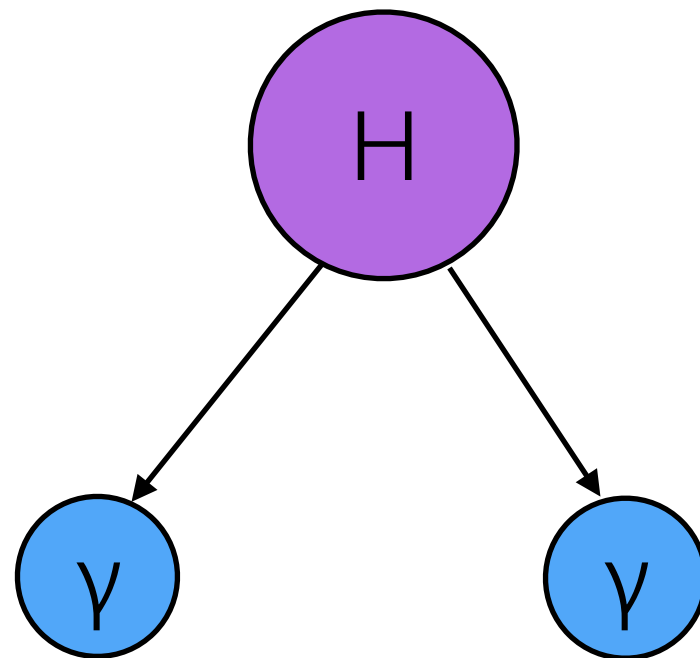
produce and decay
new particles



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

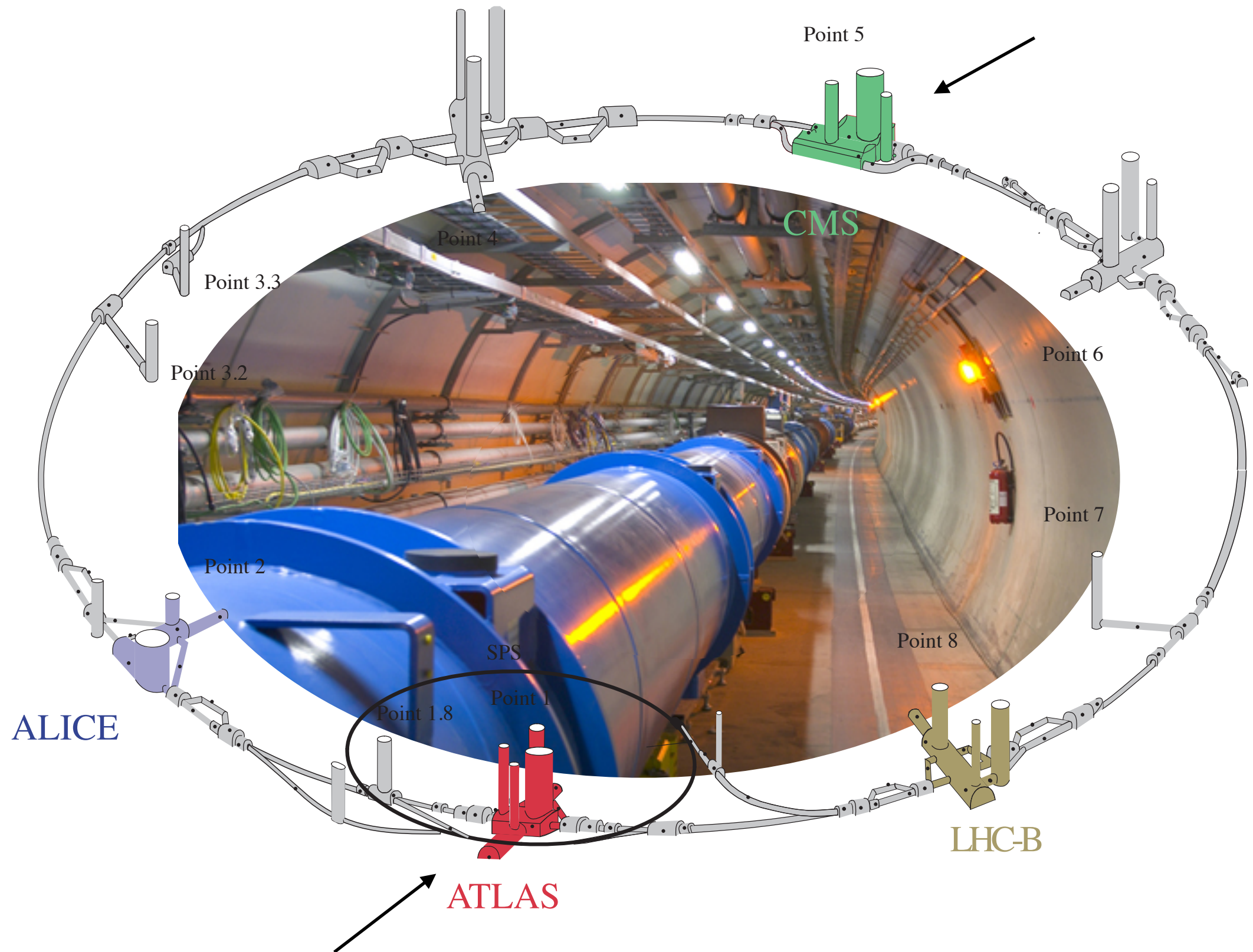
A very famous equation:

$$E = mc^2$$

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

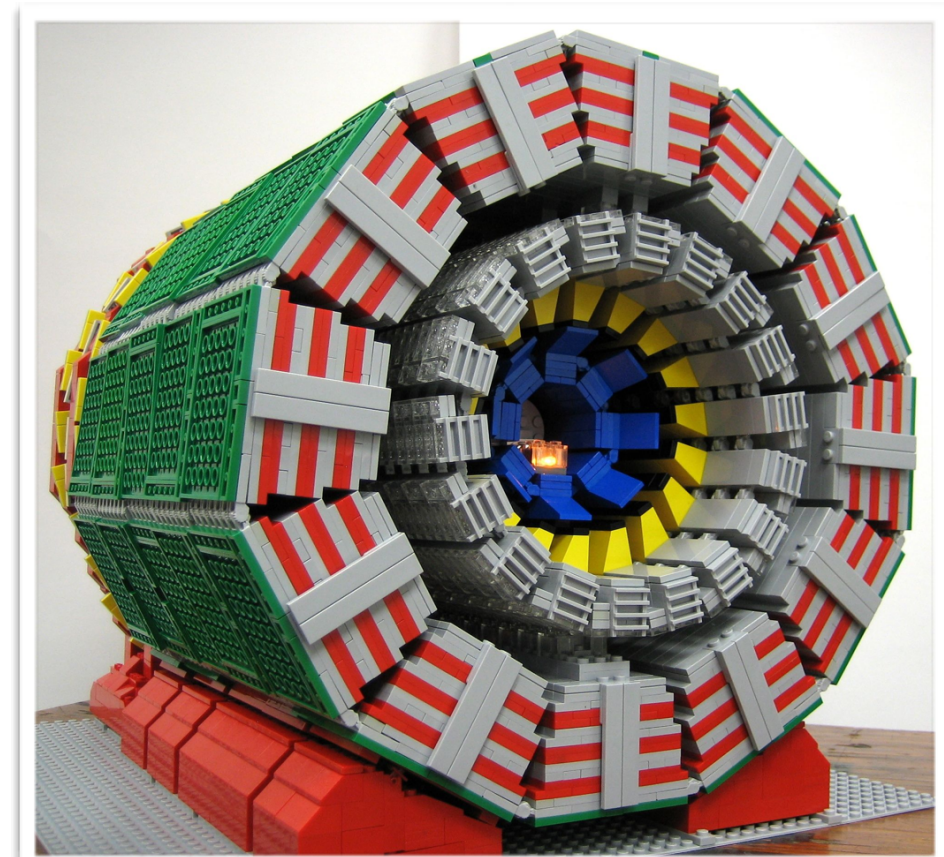
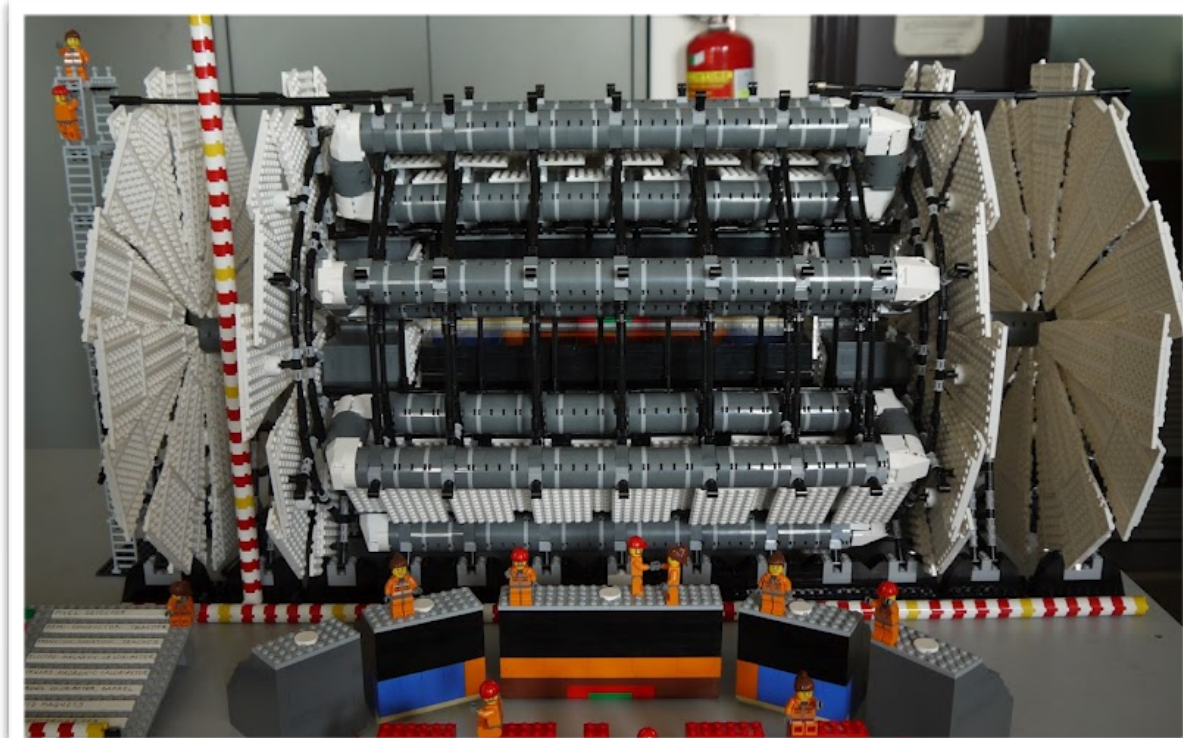
The LHC and its experiments



The Detectors

ATLAS

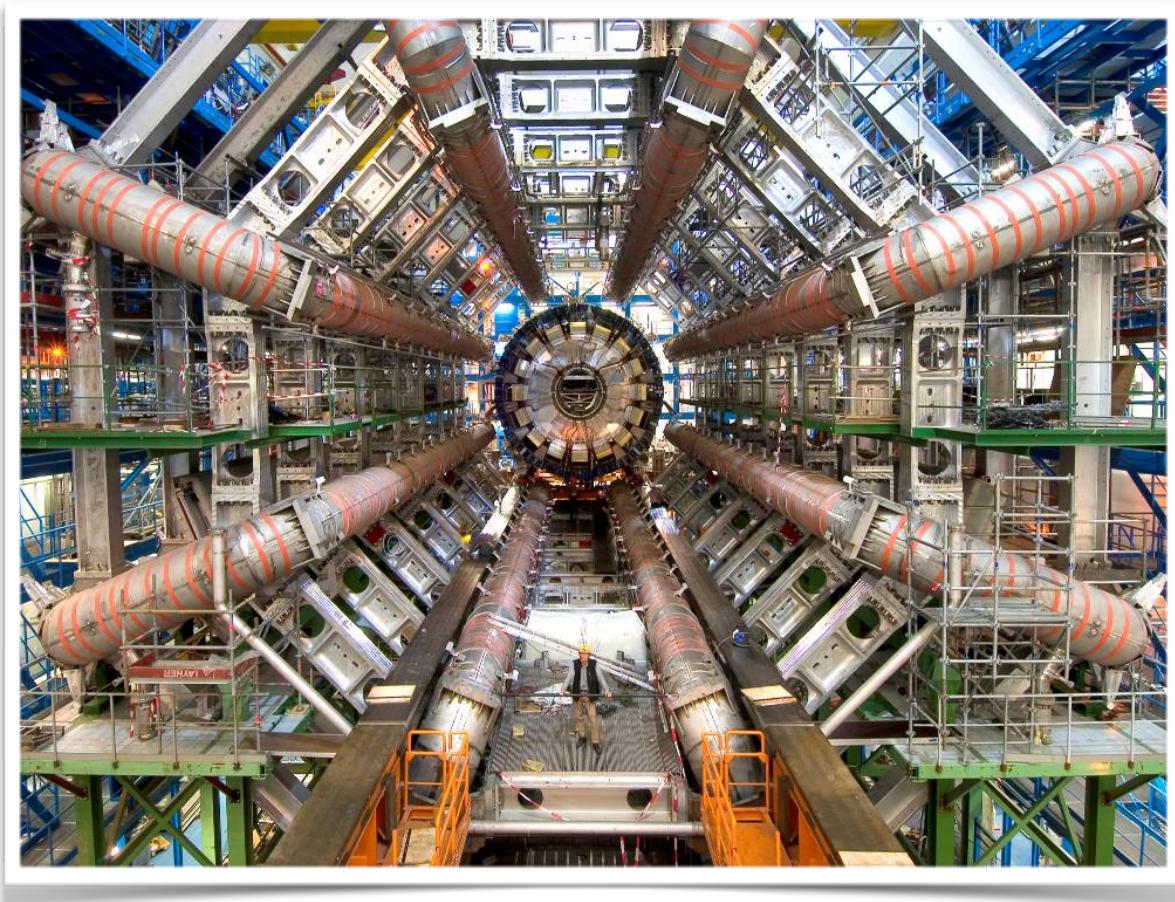
CMS



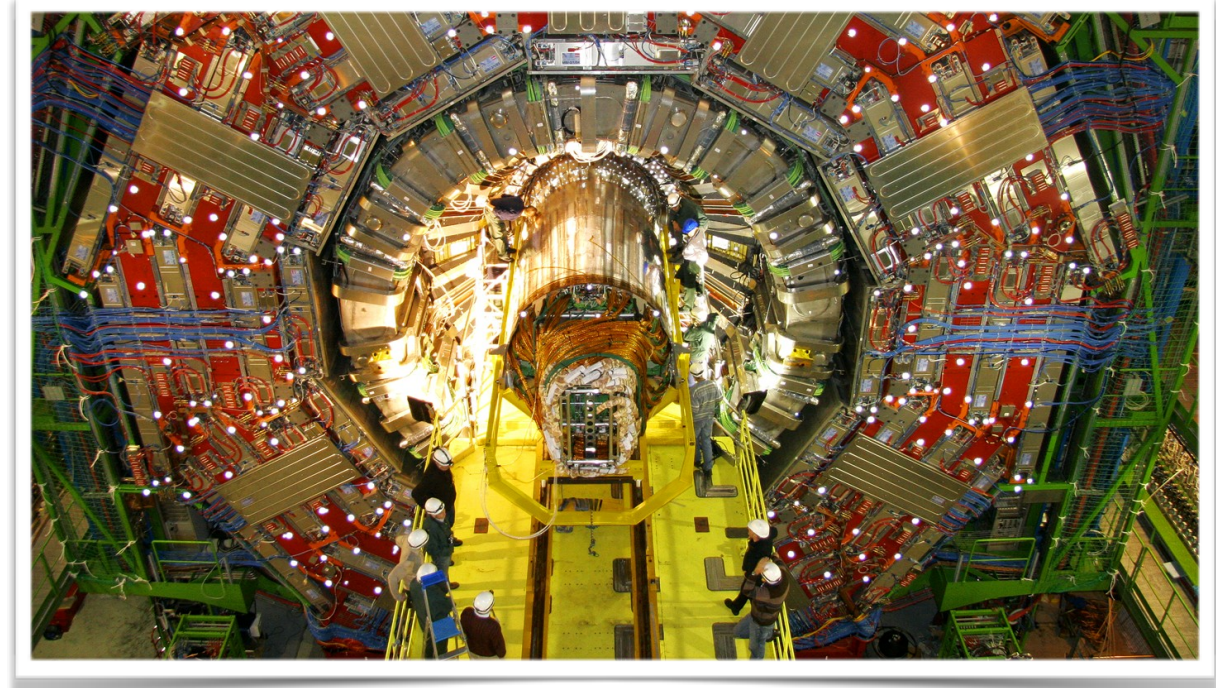
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

The Detectors

ATLAS



CMS

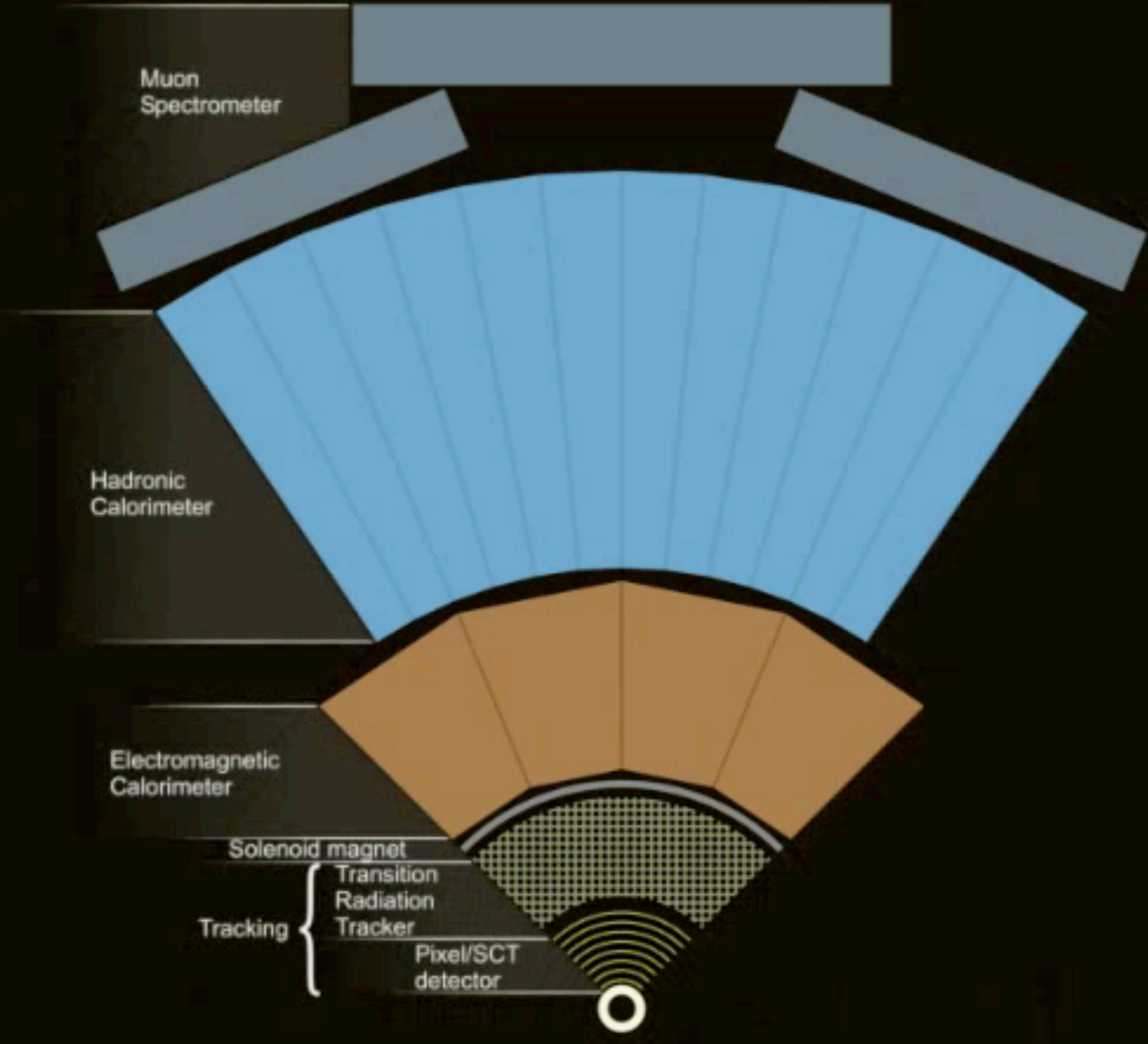


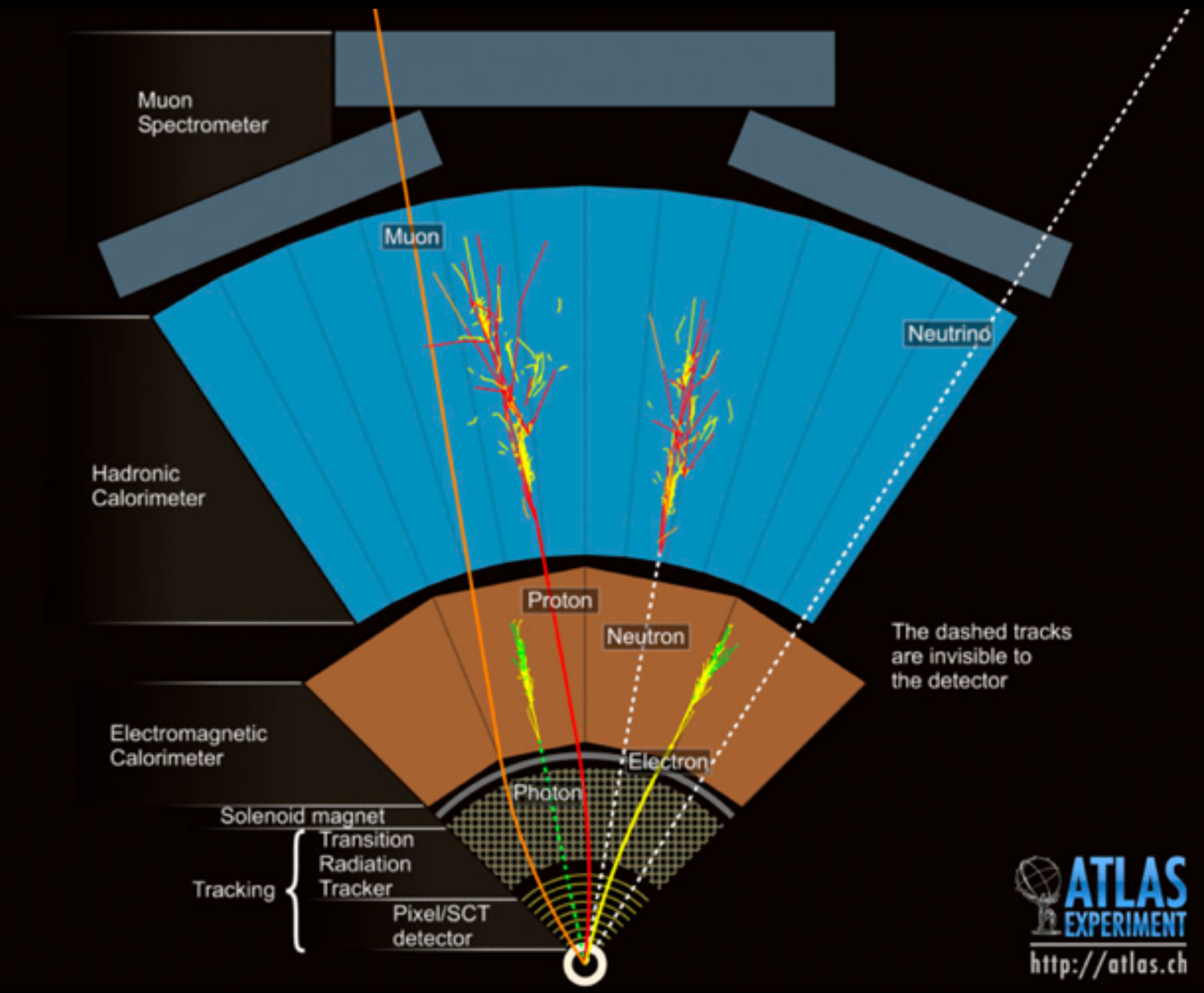
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

Particle Detectors are like onions

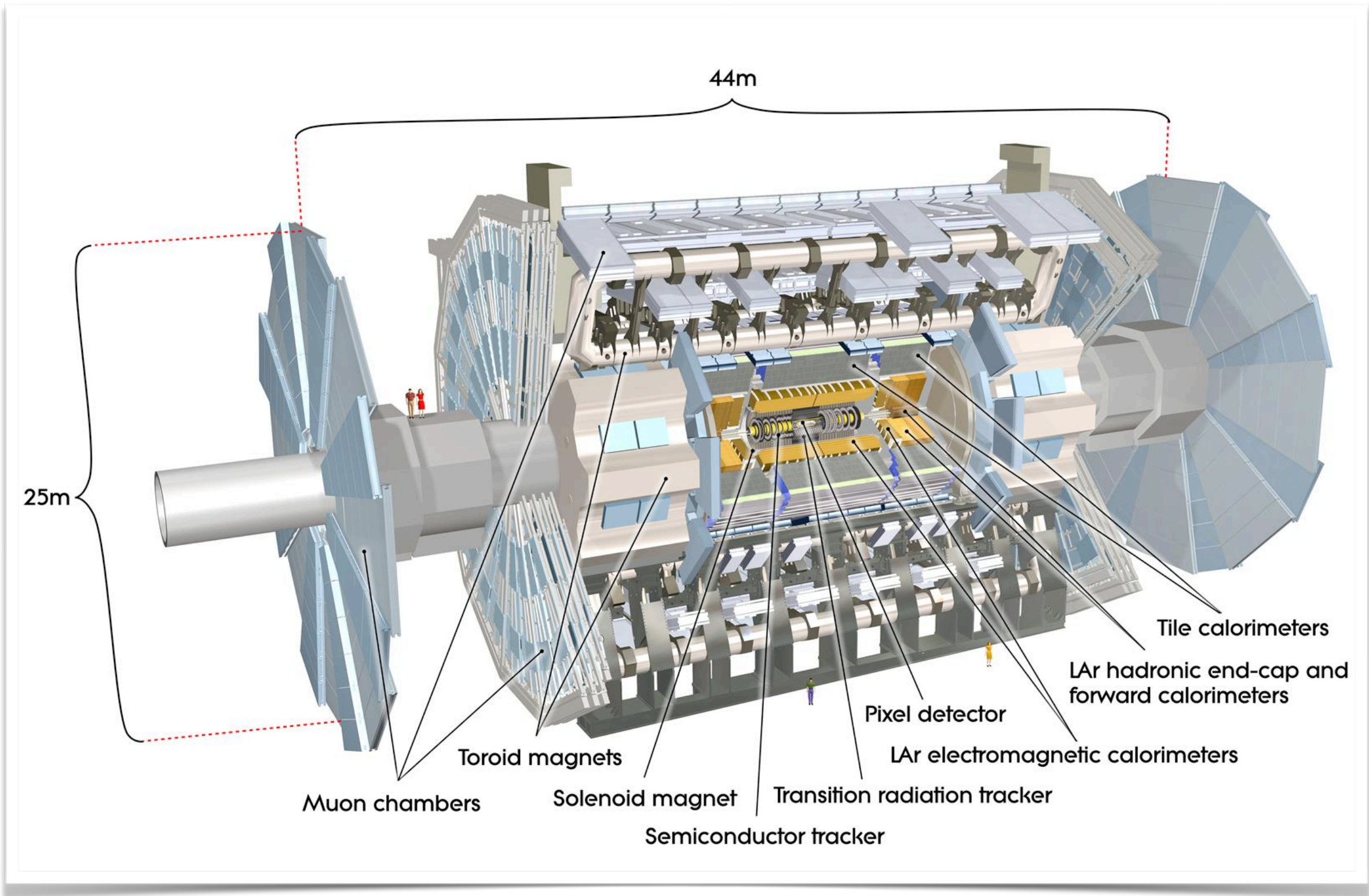
Different technologies in different layers to detect different particles: electrons, photons, protons, neutrons, “neutrinos”







A Large Toroidal Apparatus (ATLAS)



The Compact Muon Solenoid (CMS)

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

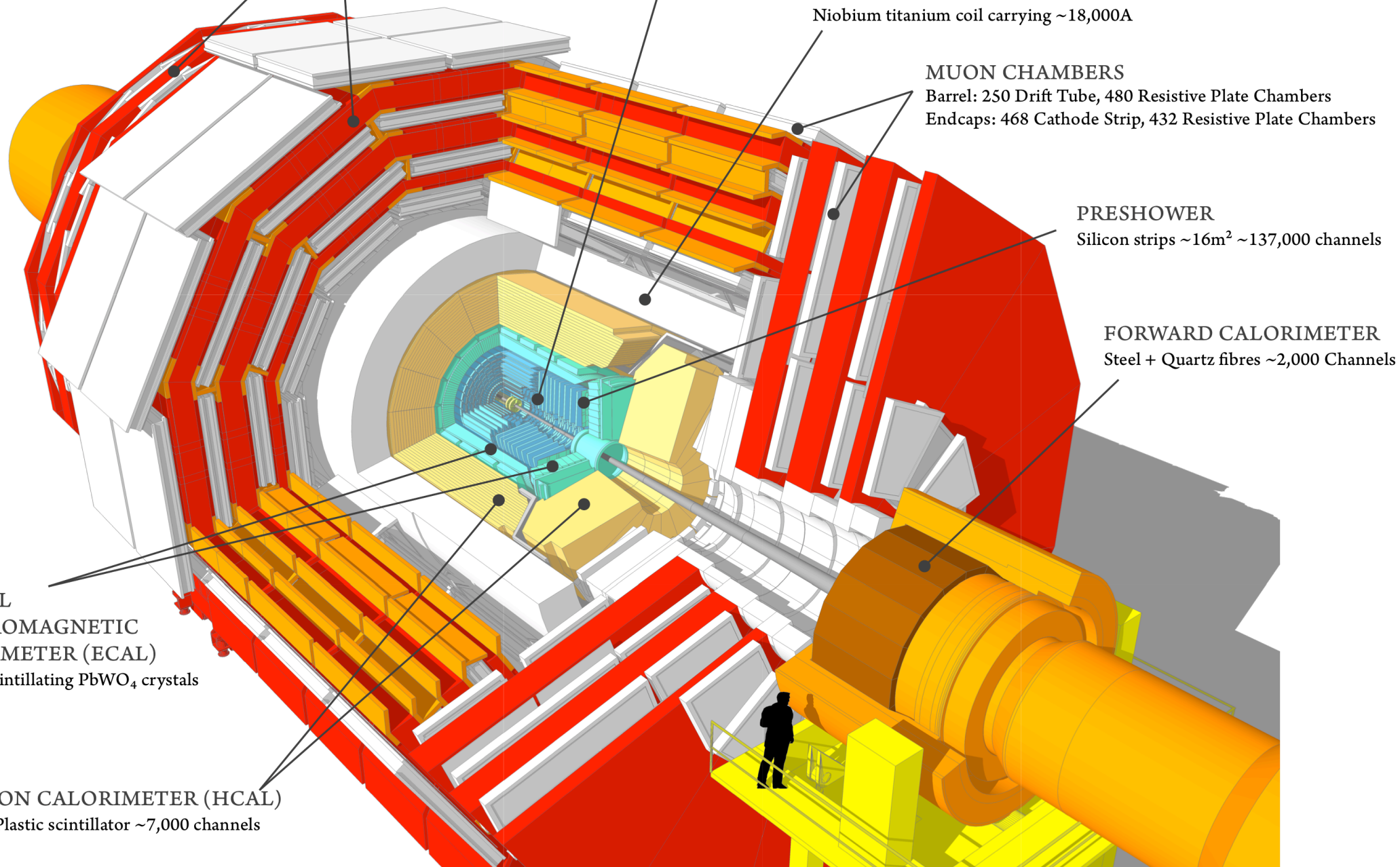
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

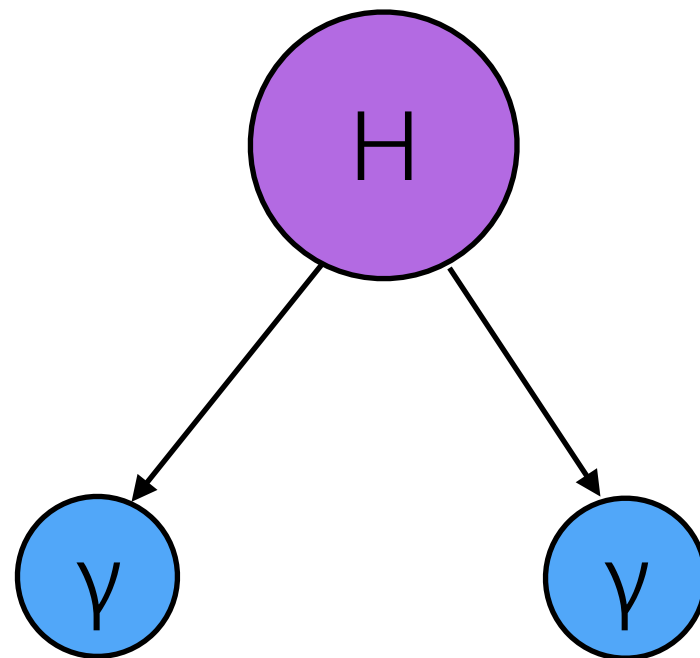
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



Seeing particles: e.g the Higgs

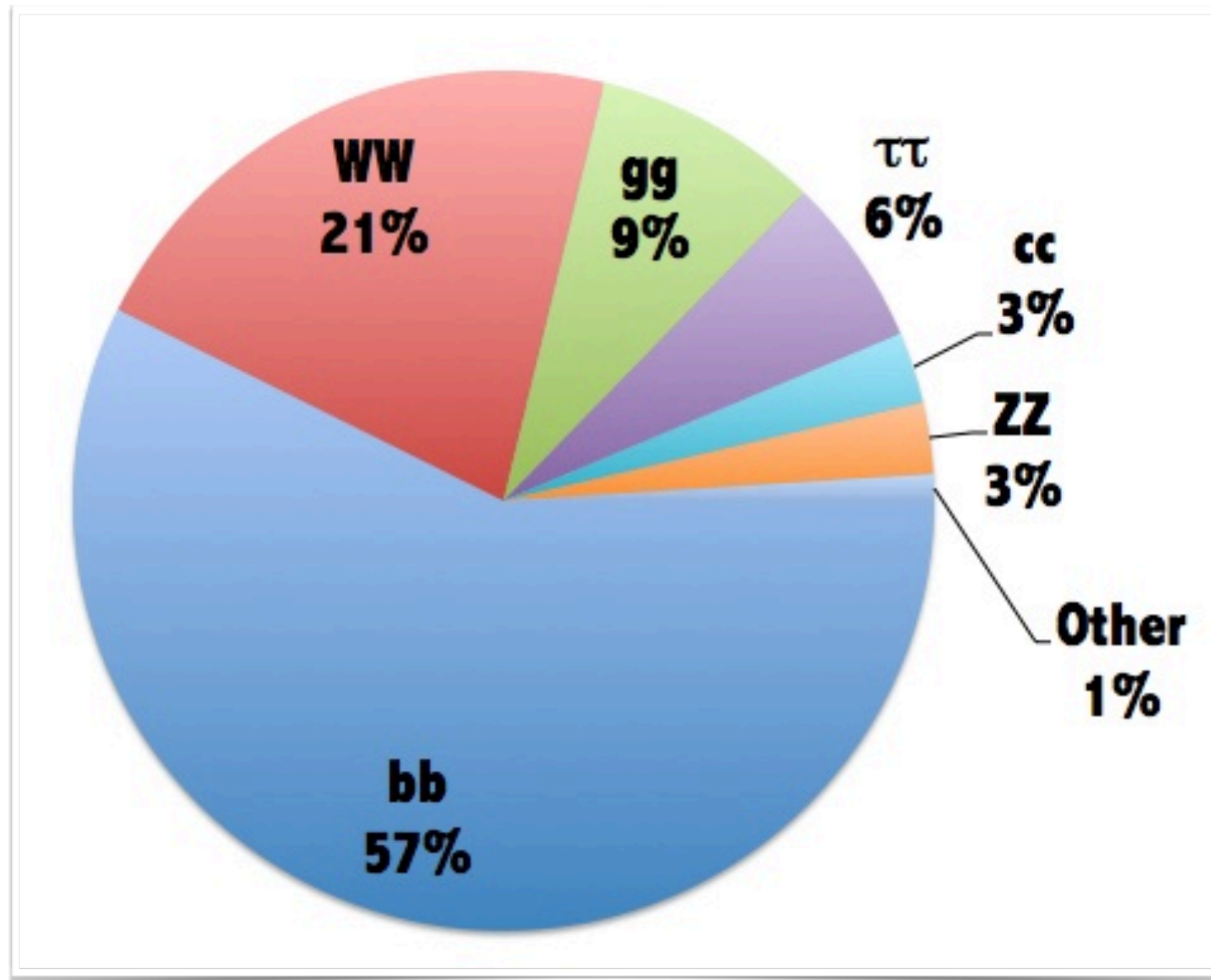
Highly unstable elementary particle!

Lifetime is only 1.6×10^{-22} s



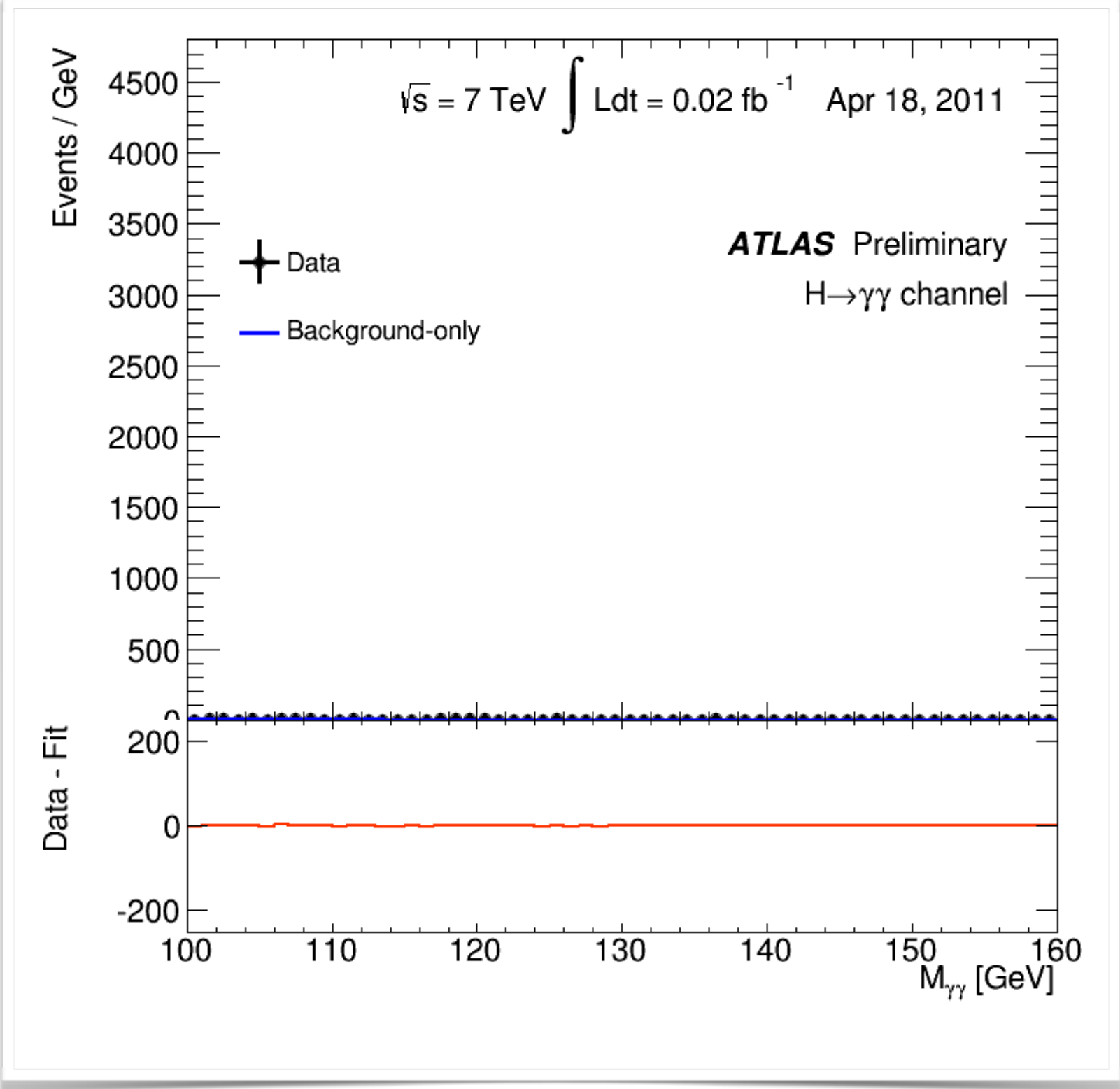
See the Higgs by studying the particles that are produced when it decays

Higgs Decays

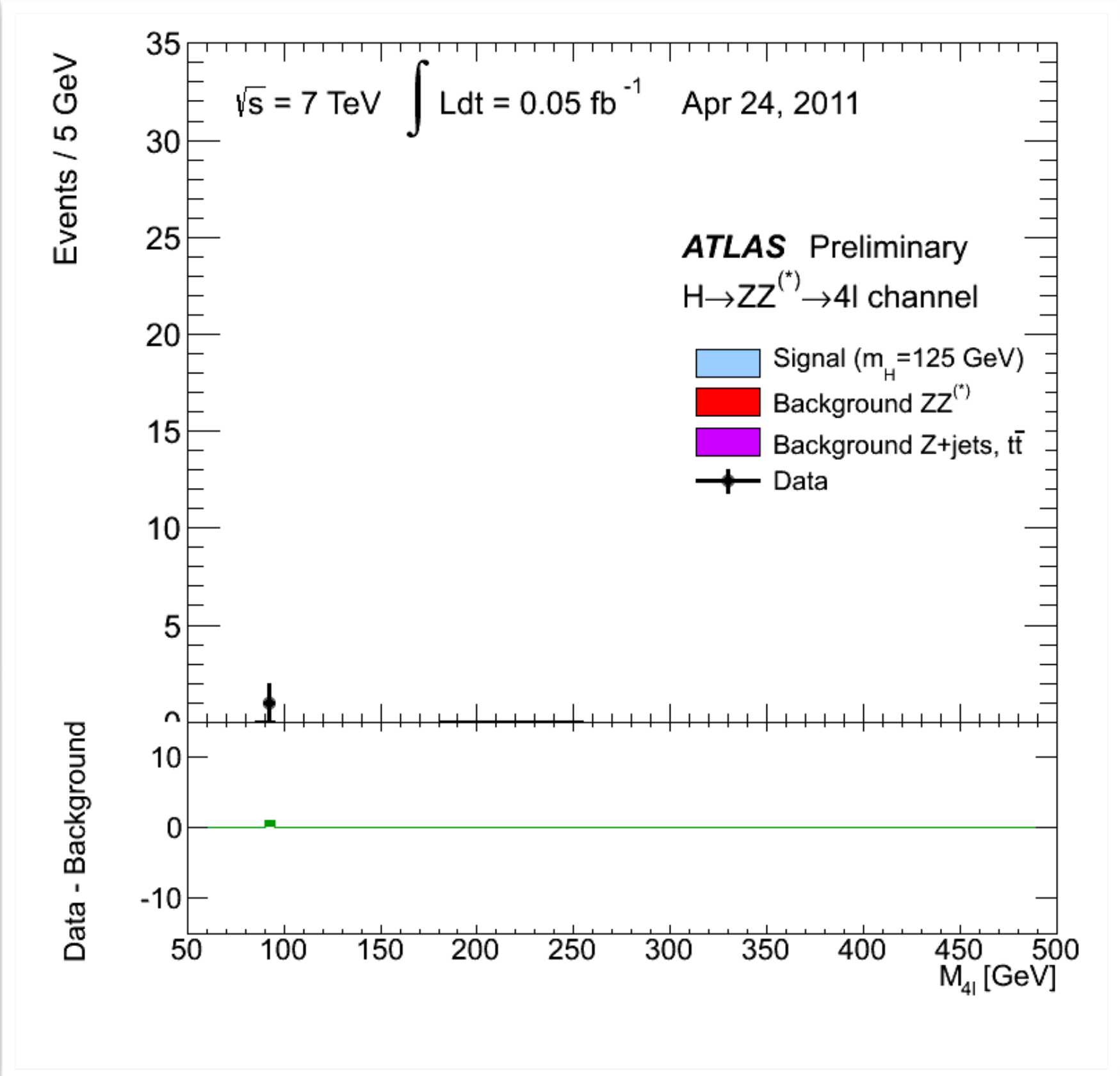


Higgs decays to any particle that has mass

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



Higgs to 4 leptons ($H \rightarrow ZZ^* \rightarrow llll$)



4 July 2012: Higgs (In)dependence Day

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• Main analysis is a Multi-Variate-Analysis (MVA)

- MVAs for photon ID and event classification
- Fit mass distribution in 4 event classes based on a diphoton MVA output + 2 0-jet categories
- Improvement in expected limit $\sim 35\%$ over cut-based analysis
- Cross-checked with an alternative background model extraction:
 - Fit output of a 2nd MVA combining diphoton MVA and $m_{\gamma\gamma}$ using data in mass sidebands to construct the background model
- Also cross-checked with a cut based analysis
 - Simple and robust
 - Cut based photon ID and event classification
 - Fit data mass distribution in 2 rapidly x 2 shower shape 4 categories with different Signal over Background (S/B) + 2 0-jet categories
- Published for 2011 data
 - Phys.Lett. B750 (2012) 409-435 arXiv:1202.5477

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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 !



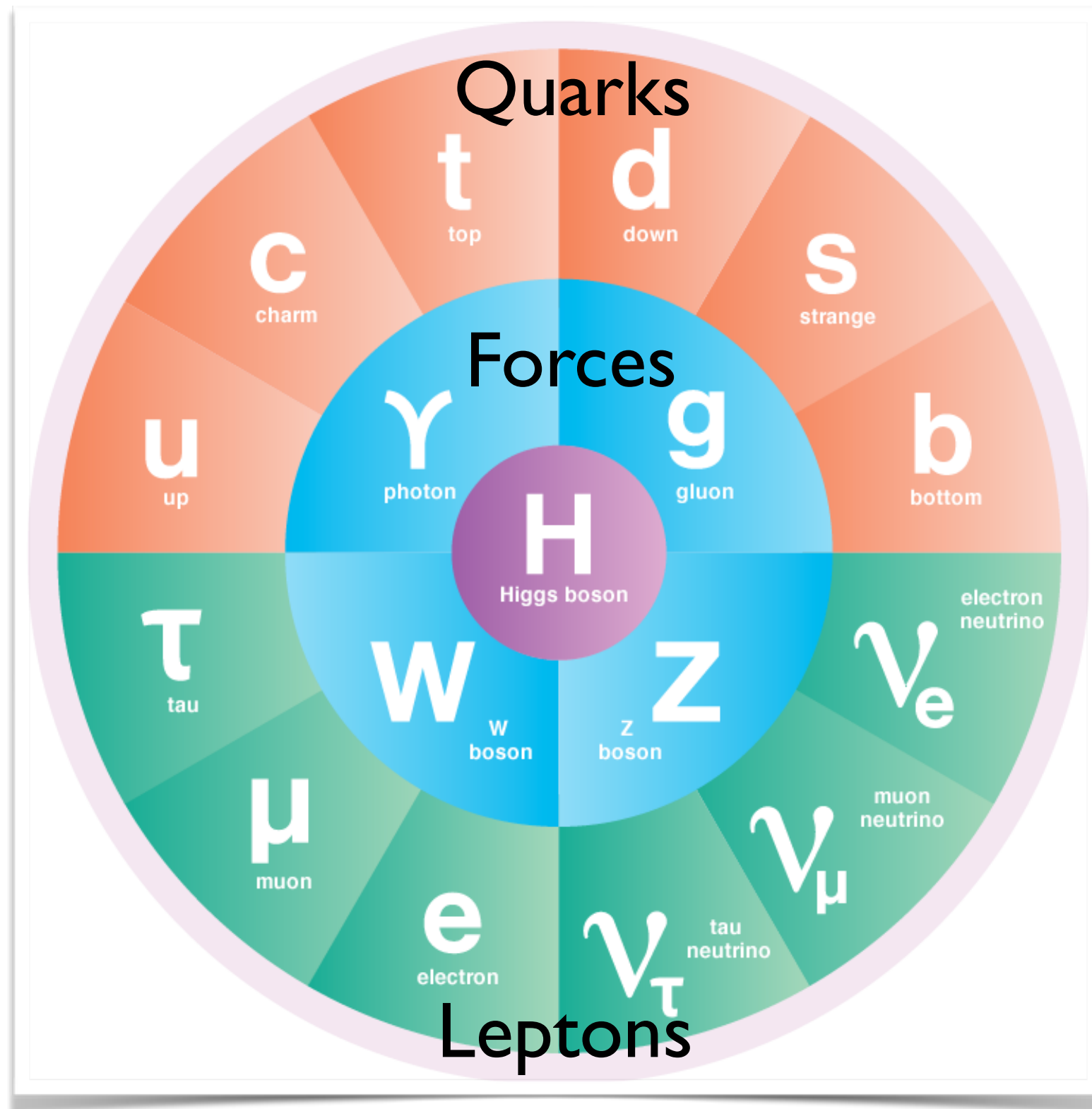


Nobel Prize in Physics 2013

to

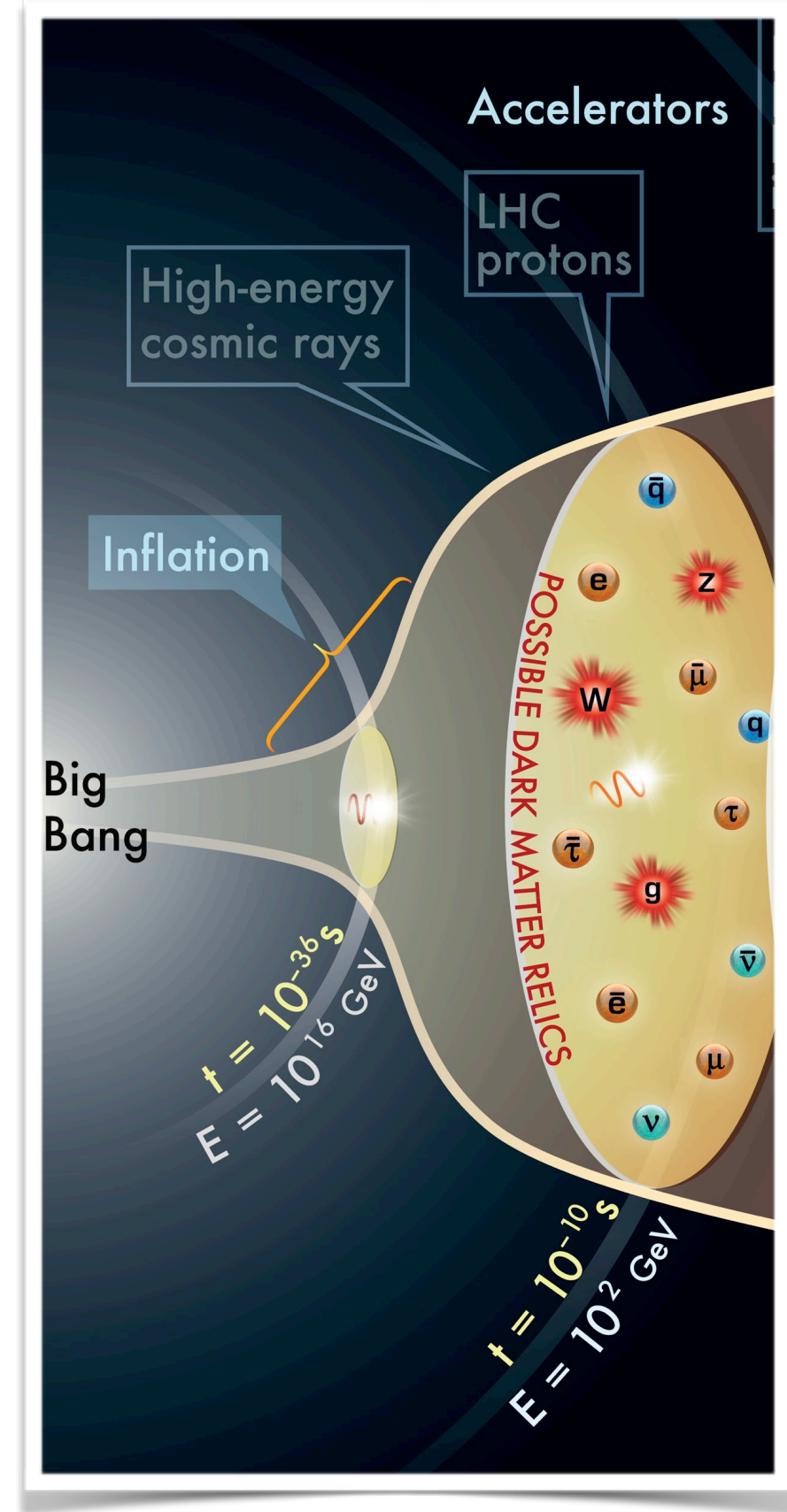
**Peter Higgs
François Englert**

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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