The Glory of Elementary Particle Physics

C.-P. Yuan
Michigan State University

@PHY 215, MSU
Nov 2025

The Glory of

Elementary Particle Physics

C.-P. Yuan

Michigan State University, USA

August 5-10, 2019 @

The 22nd WCS Science Camp

Shanlinxi, Taiwan

The connection between Cosmology and Particle Physics

- Today's Universe

  ``Dark'' Universe

- Early Universe

  Deduced from the

  Standard Model of Cosmology

- Elementary Particle Physics

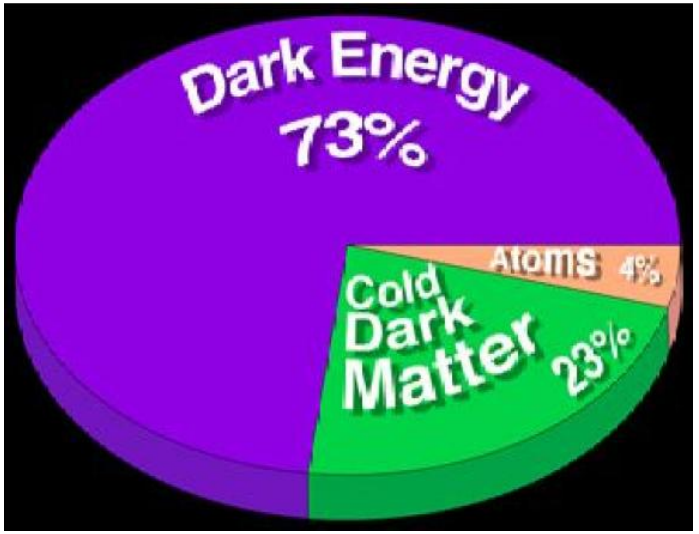
  Needed to describe the early universe.

“Dark” Universe

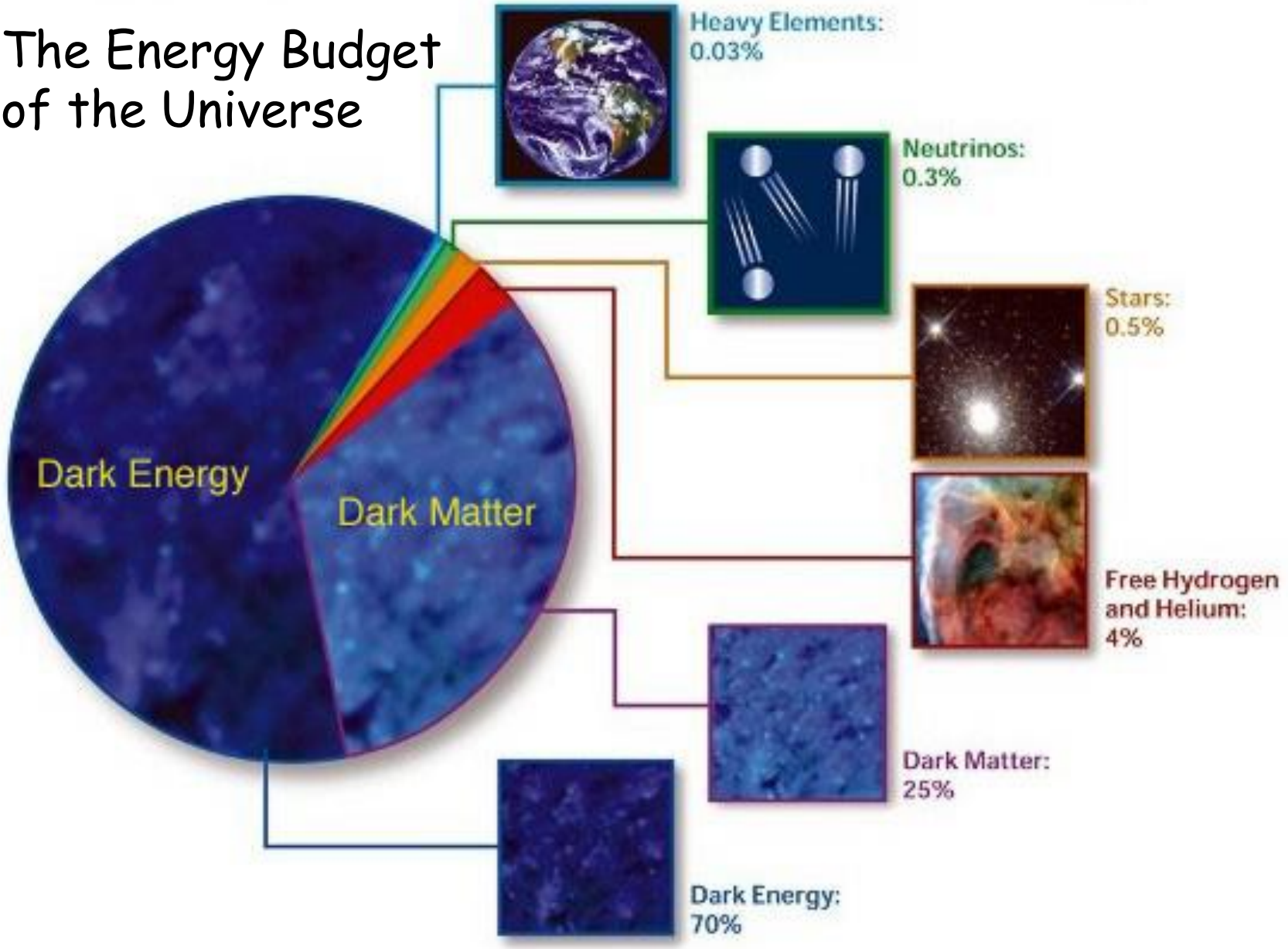
Recent astrophysics data told us that our Universe is made of :

- starts and galaxies (ordinary matter) 0.5%
- Rest of ordinary matter 4.5%
- Dark matter (not ordinary matter) 25%
- Dark Energy (filling up empty space) 70%

The “sky”
is made mostly by
something other than
ordinary matter.



The Energy Budget of the Universe



Standard Model of Cosmology
Big Bang Cosmological Model
$(\Lambda - CDM$ Model)

- General Relativity

(Einstein)

- Cosmological Principle

(The three-space of constant time are homogeneous and isotropic at all time)

- Elementary Particle Physics

(To describe particle content of the early universe)

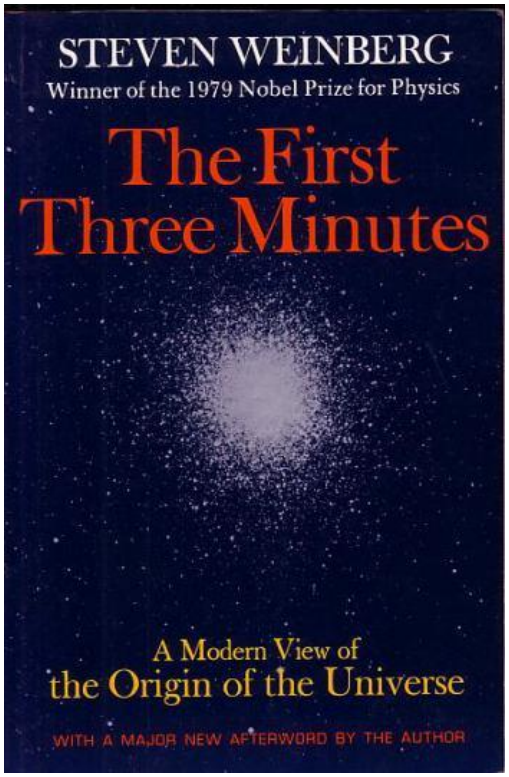
- Λ : Dark Energy
- CDM: Cold Dark Matter
- Ordinary matter: **Standard Model of Particle Physics**

Book Recommendation

The First Three Minutes

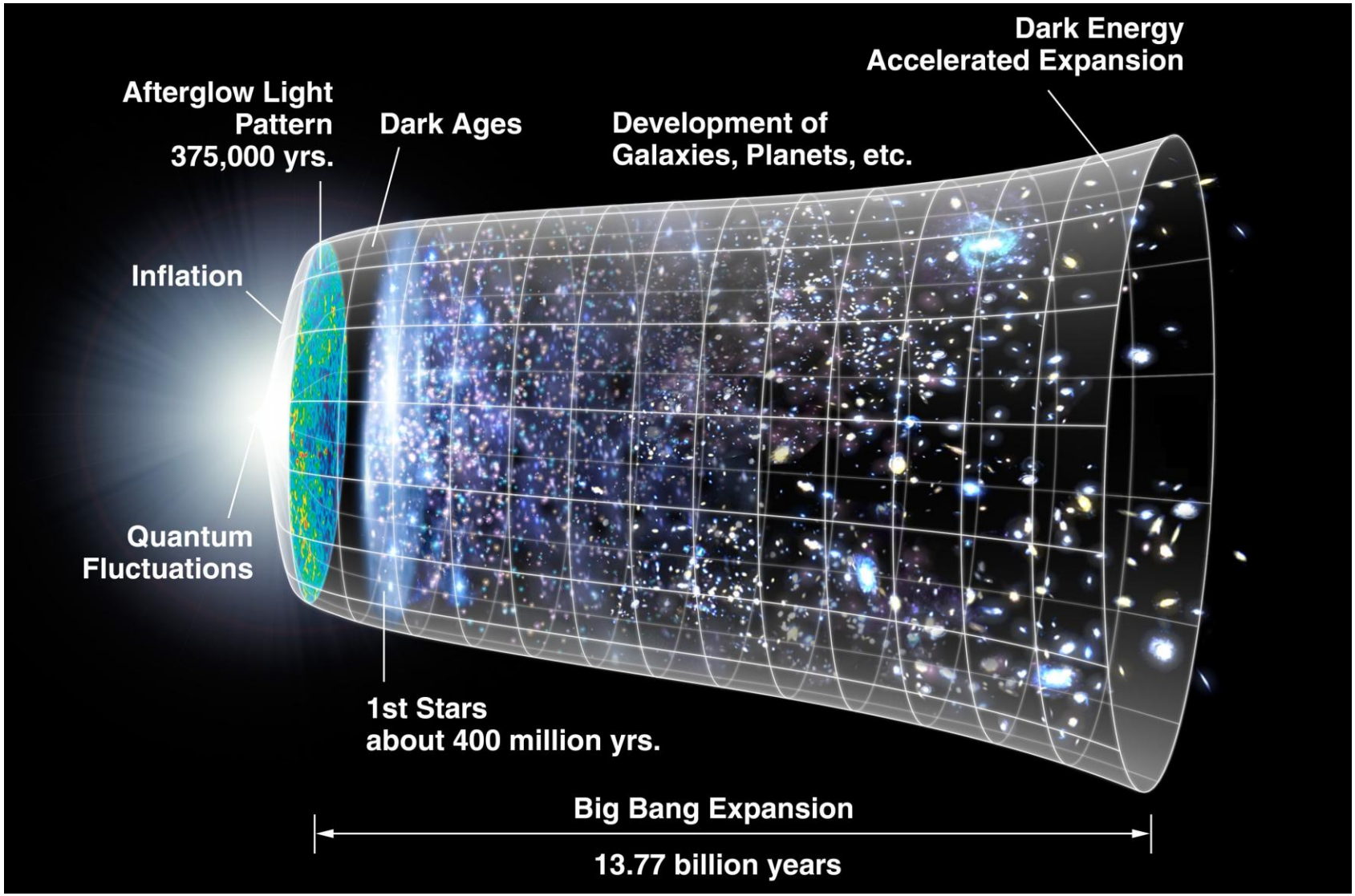
by

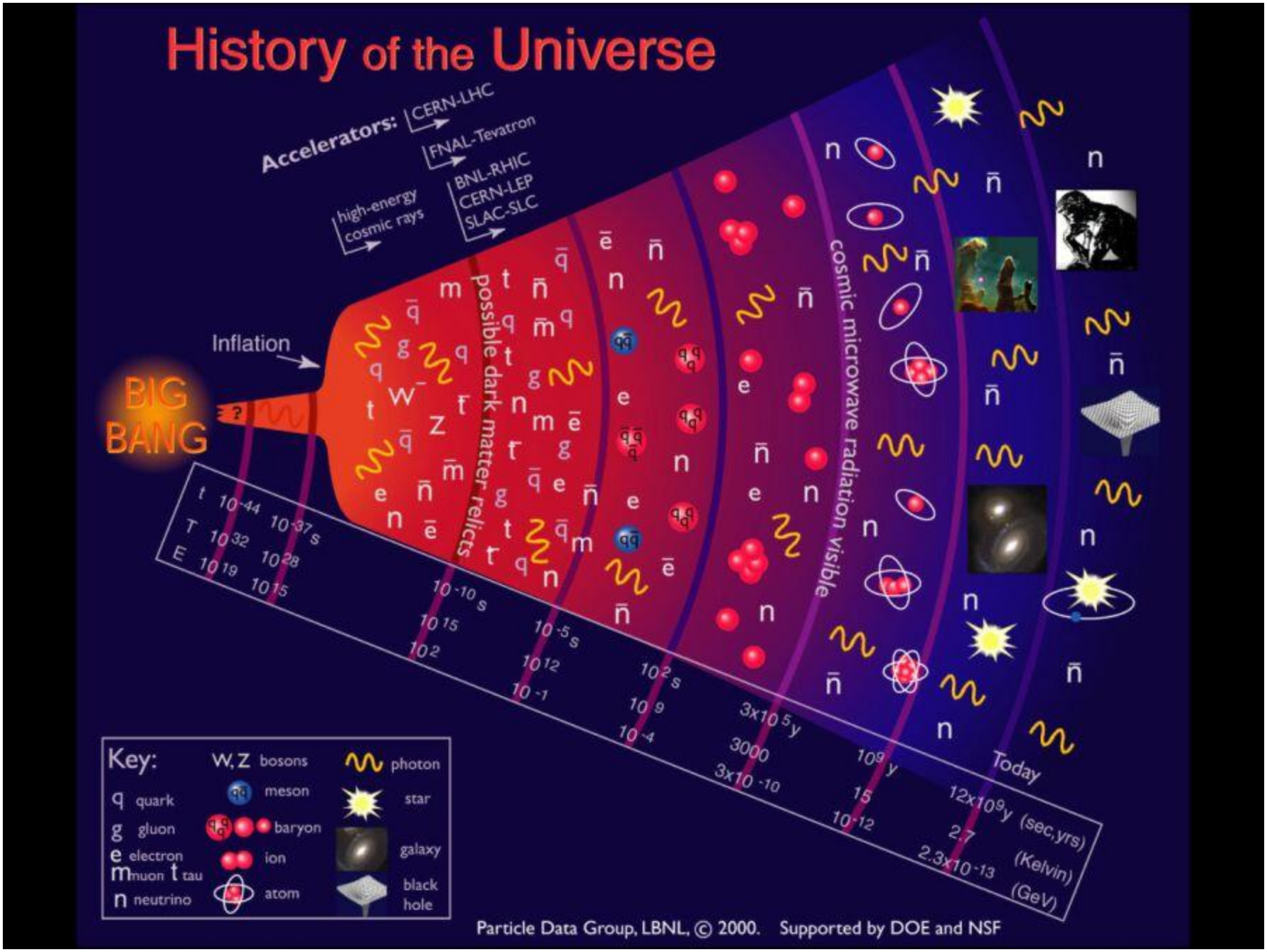
Steven Weinberg



Describes the history of the early universe, and the history of how we learned about the early universe.

Timeline of the expansion of the universe, where space is represented schematically at each time by circular sections. On the left, the dramatic expansion of inflation; at the center, the expansion accelerates (artist's concept; neither time nor size are to scale).



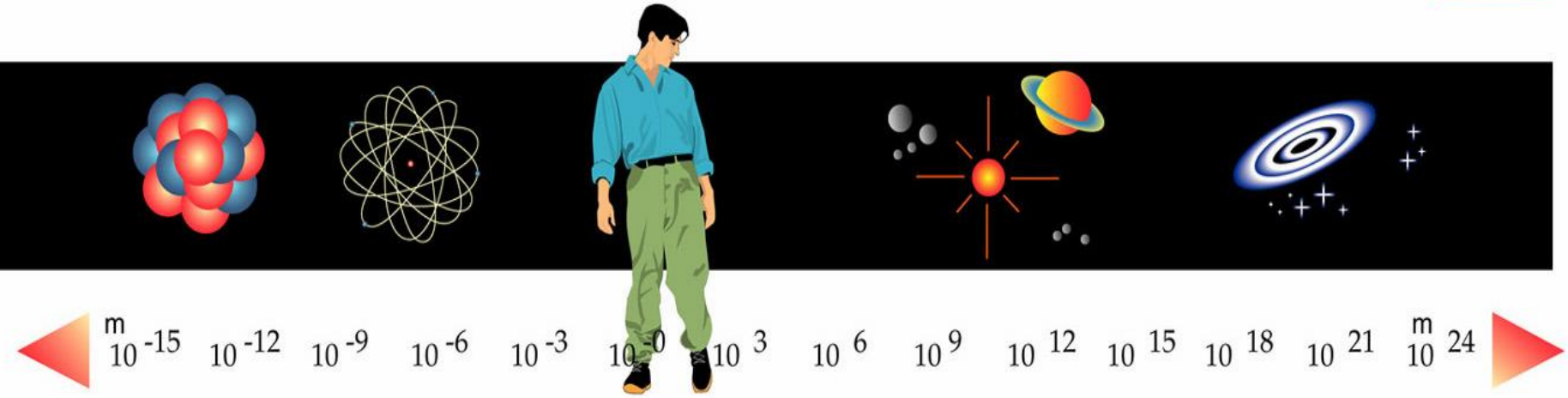

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Ultimate Time Machine

- Doing astronomical observations is like travelling back in time
- If an galaxy is 1 million light years away, then the light that you are seeing left that galaxy 1 million years ago, and you are seeing what it looked like long ago
- Do the Time Machine Activity

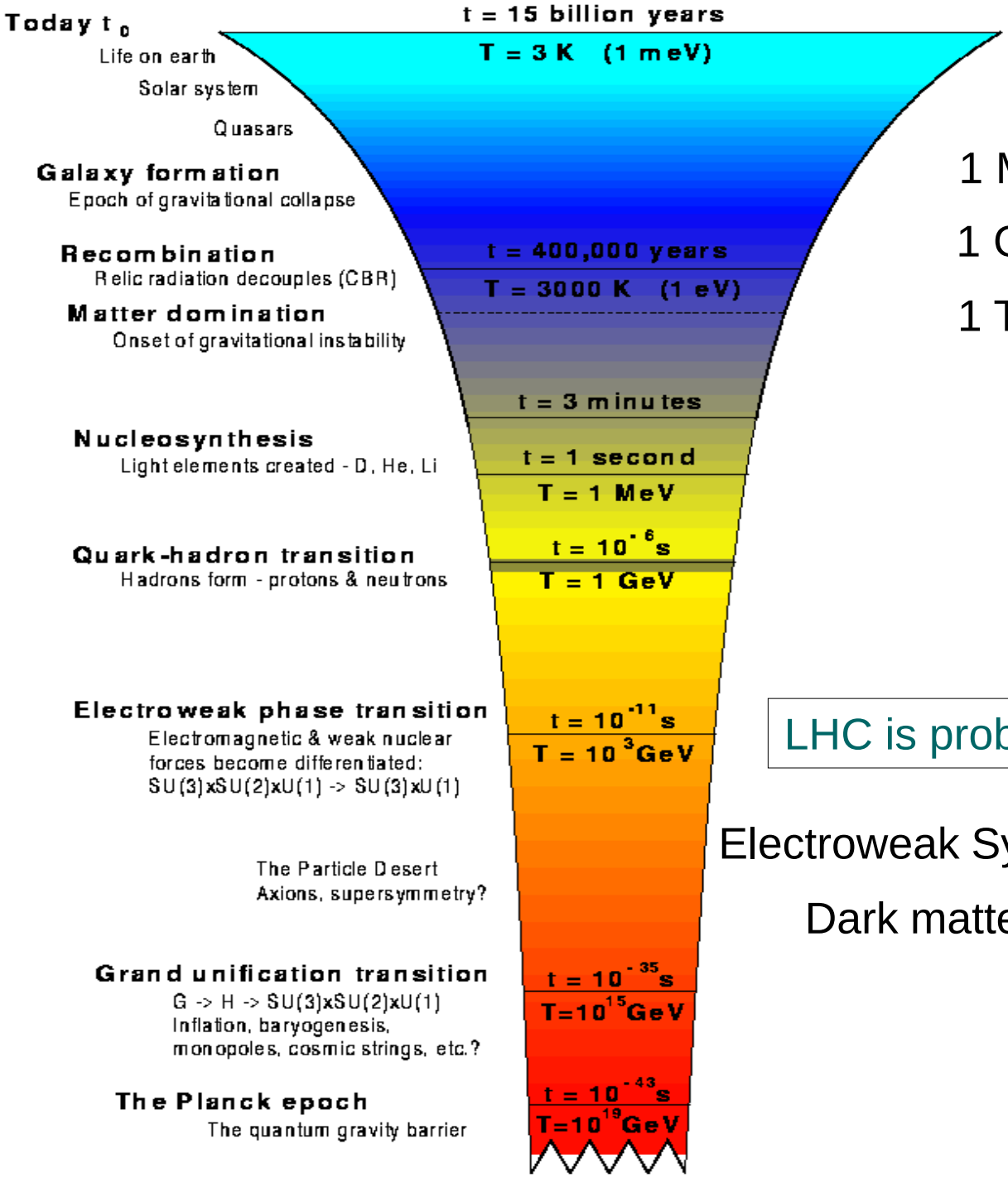
Particle physics looks at matter in its smallest dimensions.

Astrophysics looks at matter in its largest dimensions.



m
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} m 10^{24}

They are related!



1 MeV = 10^6 eV

1 GeV = 10^9 eV

1 TeV = 10^{12} eV

LHC is probing TeV region

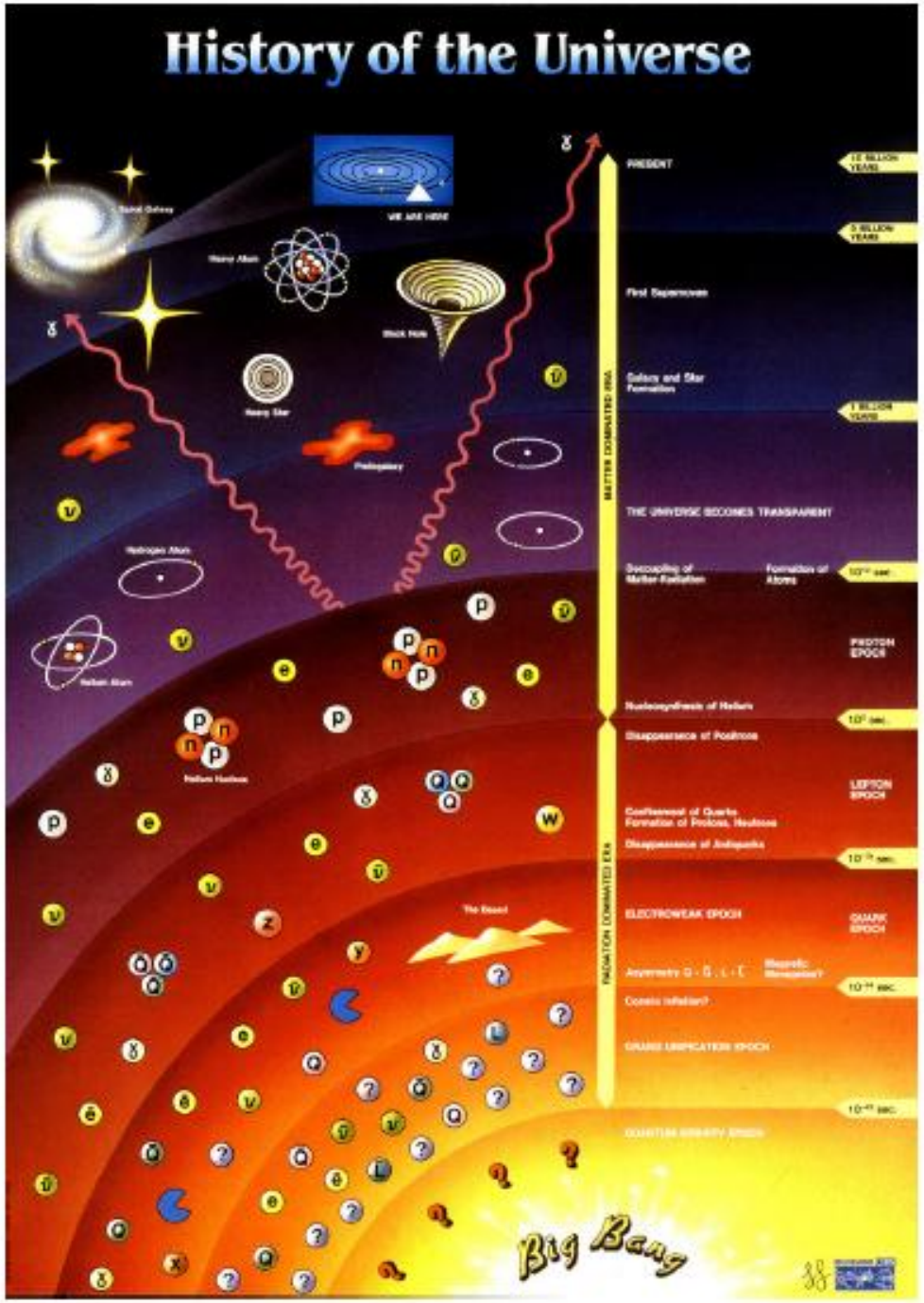
Electroweak Symmetry Breaking

Dark matter candidate

LHC recreates conditions of early universe

- Investigate matter-antimatter assymetry of universe
- Understand the origin of mass
- Might find dark matter

Particle Physics | Astrophysics

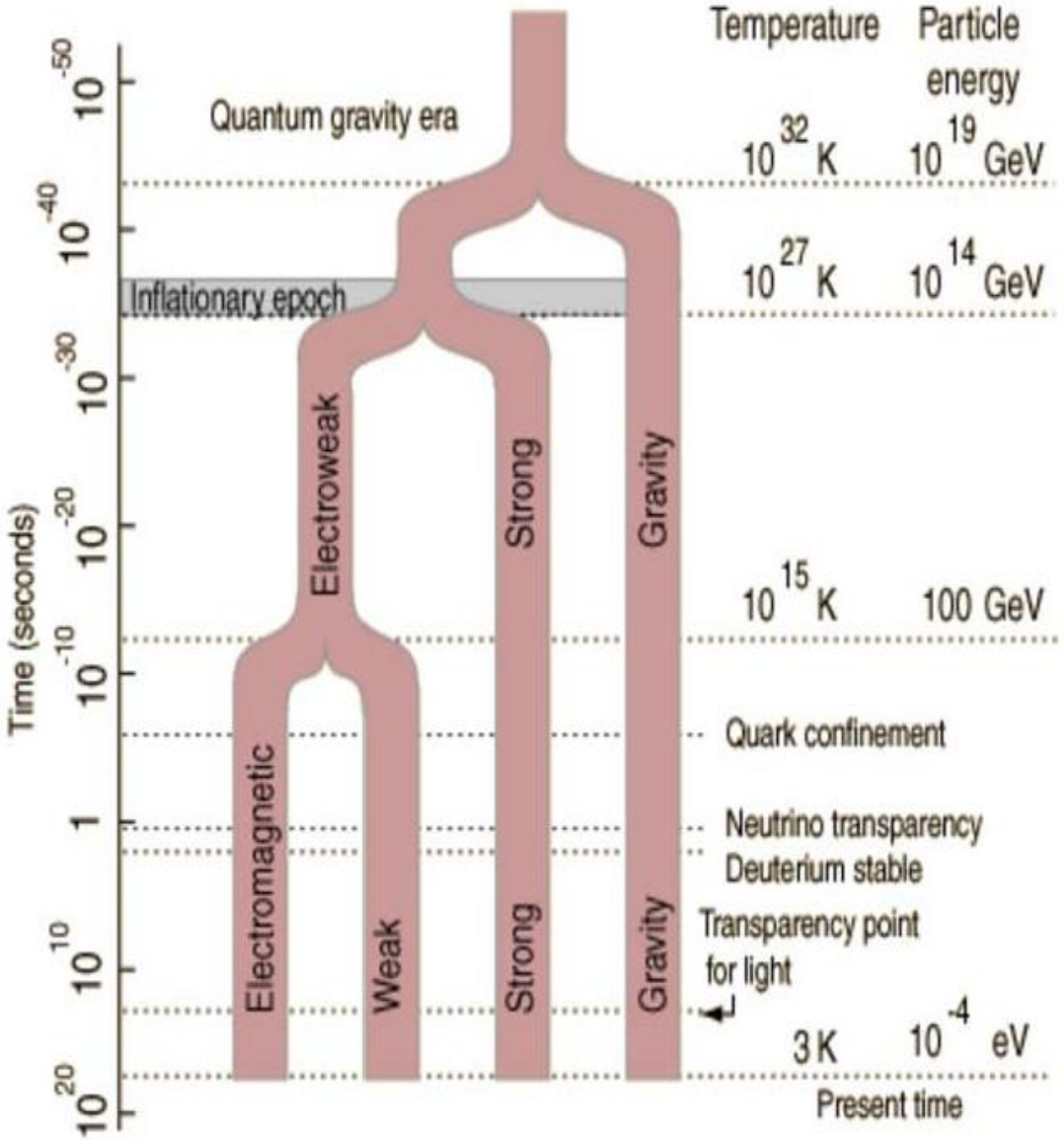


1 GeV = 10^9 eV

1 TeV = 10^{12} eV

LHC is probing TeV region

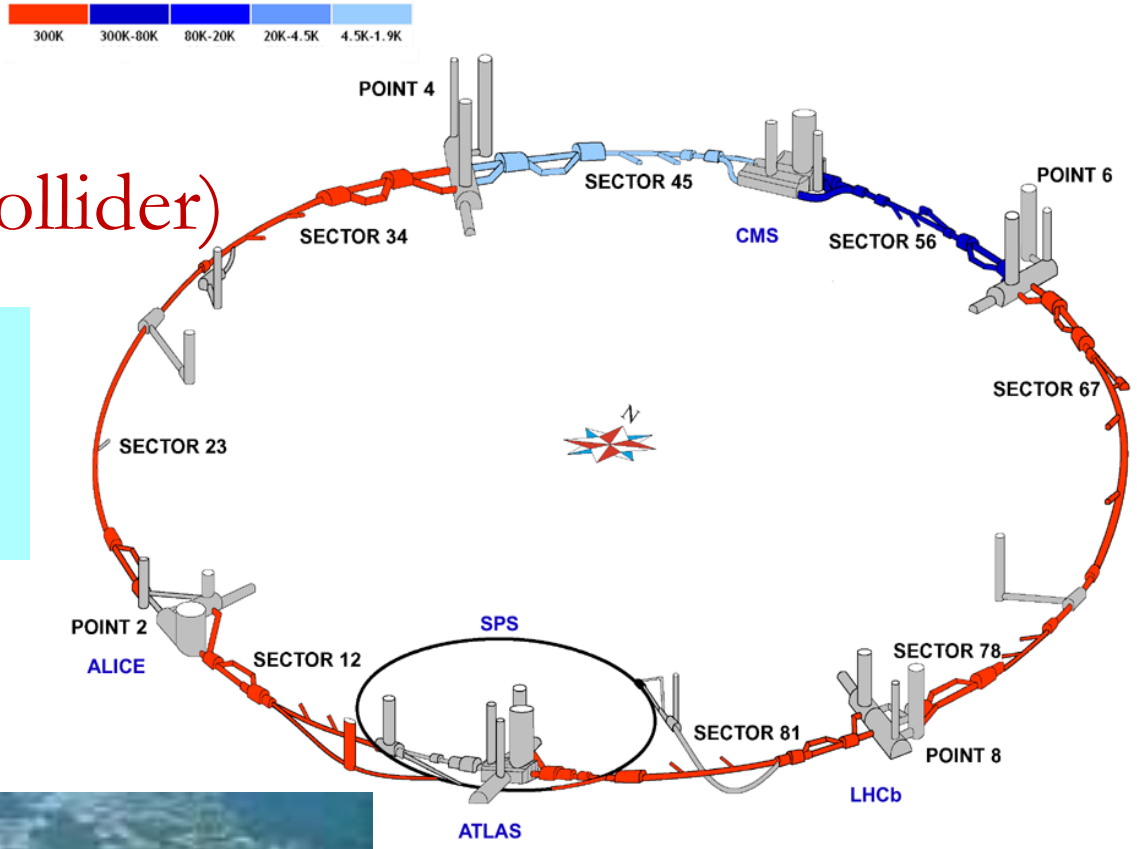
It is about
0.00000000001 second
after Big Bang,
or,
about 14 billion years ago.



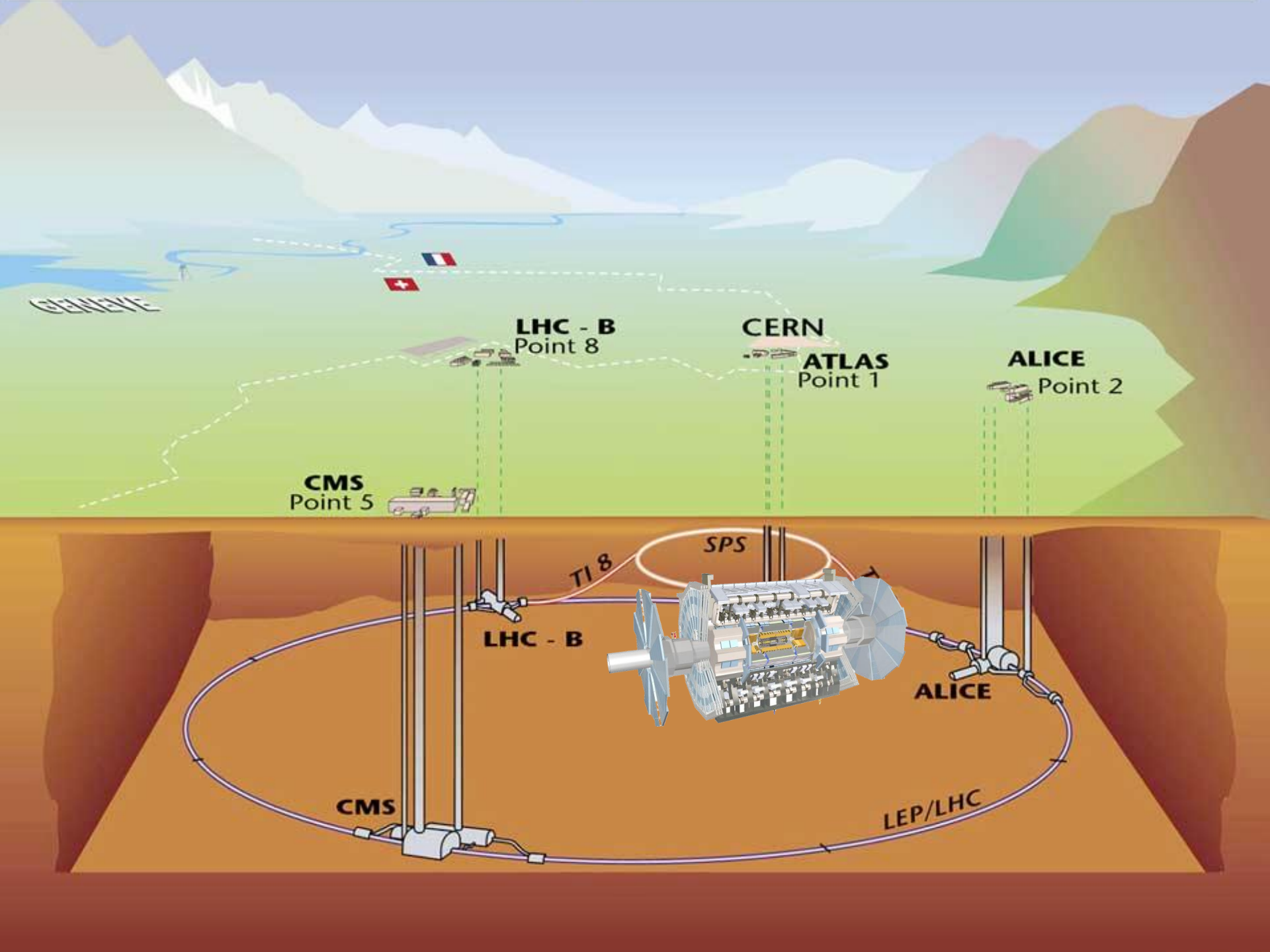
Early universe chronology

CERN LHC
(Large Hadron Collider)

The highest energy
Proton-proton collider
In the world.



The Large Hadron Collider (LHC) is a 27km long circular accelerator built at CERN, near Geneva Switzerland. The tunnel is buried around 50 to 175 m underground.


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
LHC - B
ALICE
CMS
LEP/LHC

Elementary Particle Physics

To answer

What are the Elementary Constituents of Matter?

What are the forces that control their behaviour at the most basic level?

Science Is About Simplification

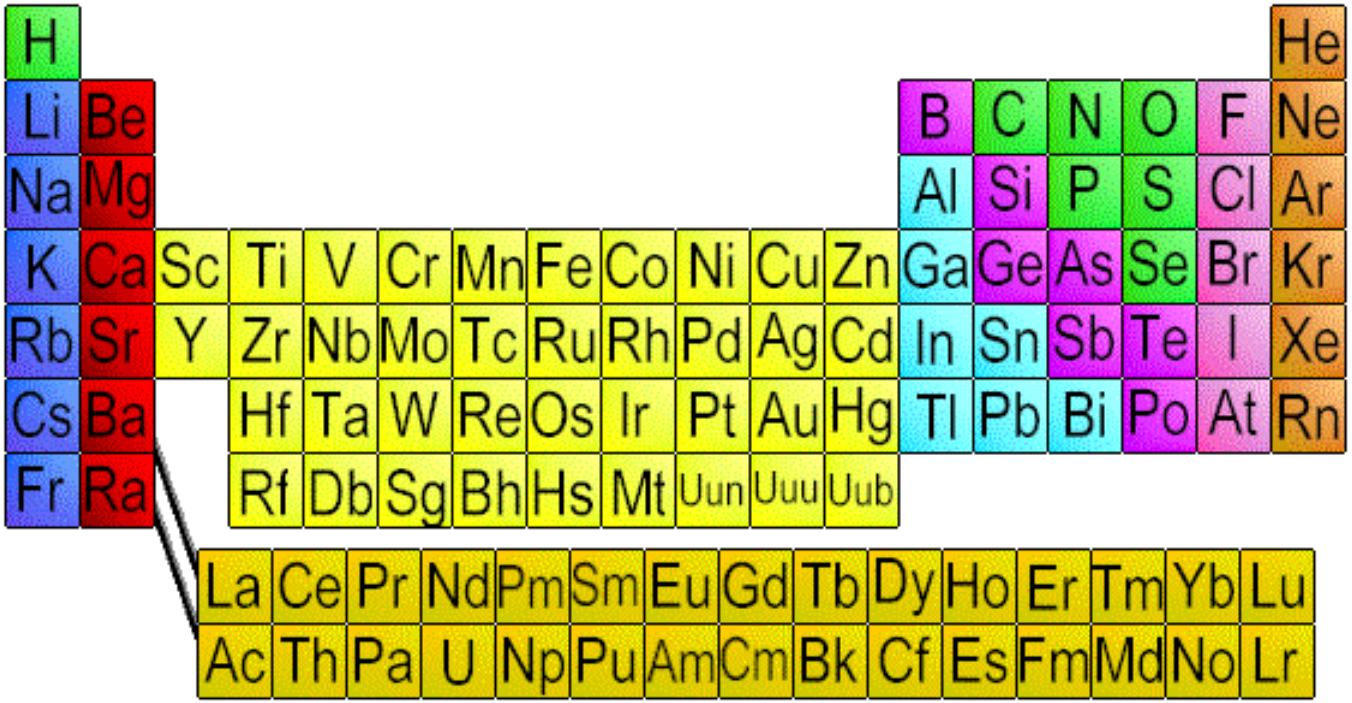
- Why do so many things in this world share the same characteristics?
- People have come to realize that the matter of the world is made from a few fundamental building blocks of nature.

("Fundamental" here means simple and structureless --- not made up of anything smaller.)

What is the Ultimate Structure of Matter?

- In 1900's the fundamental particle is atom

But, is the atom fundamental?

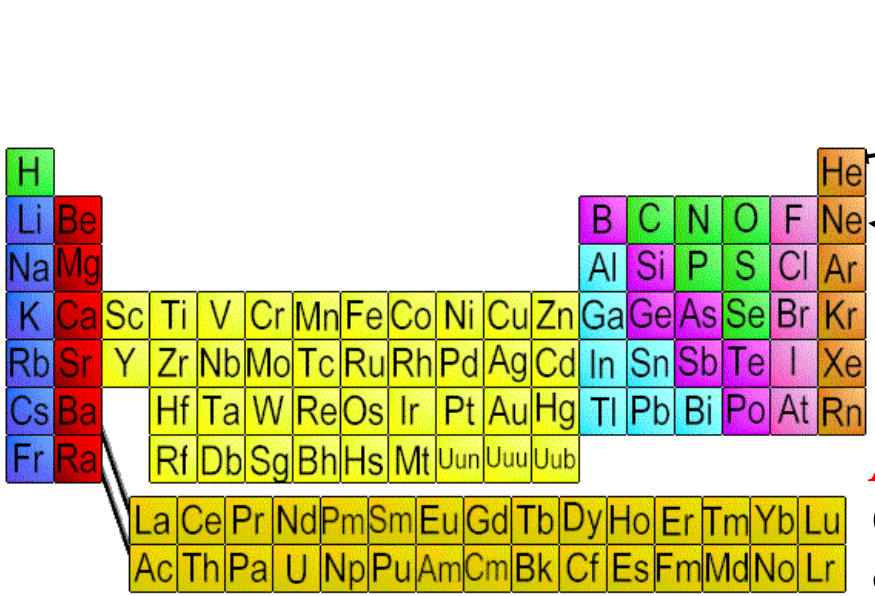


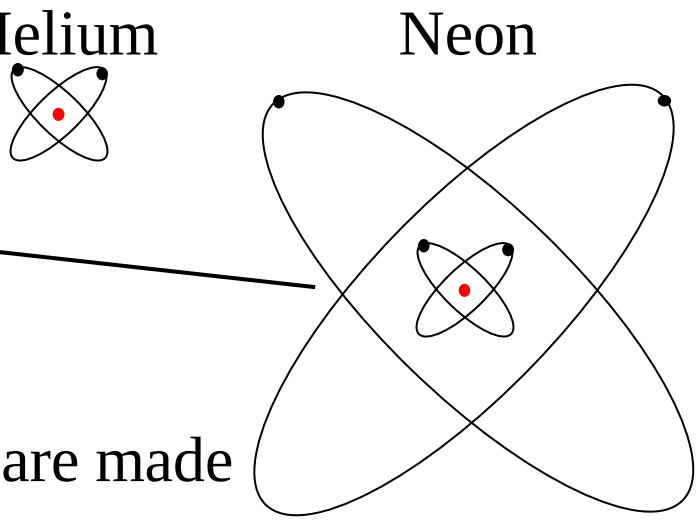
- Periodic Table of Elements (Atoms could be categorized into groups that shared similar chemical properties) suggest:

  atom has substructure!

Nuclei and electron

- Atoms are made up of simpler building blocks:



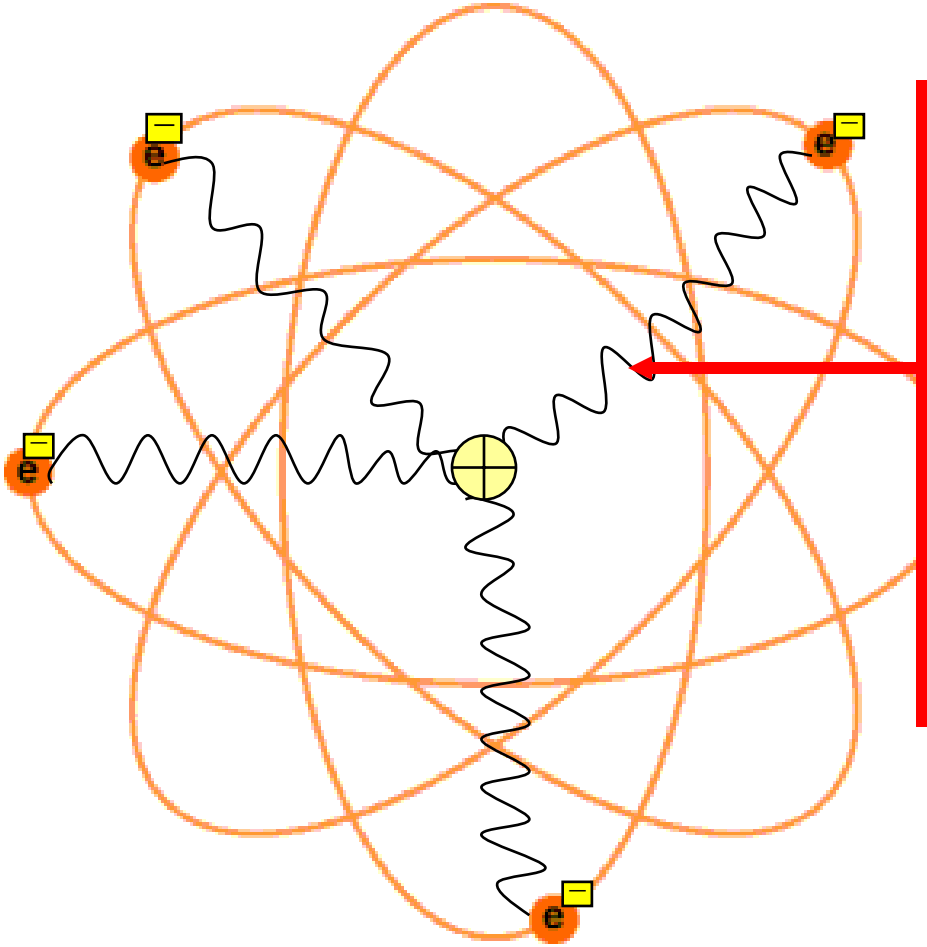


All atoms are made of Nuclei and orbital electrons

Photons hold atom together

Usually we call the electromagnetic interaction between nuclei and electron "Columb force"!

The quanta of the electromagnetic force is photon.



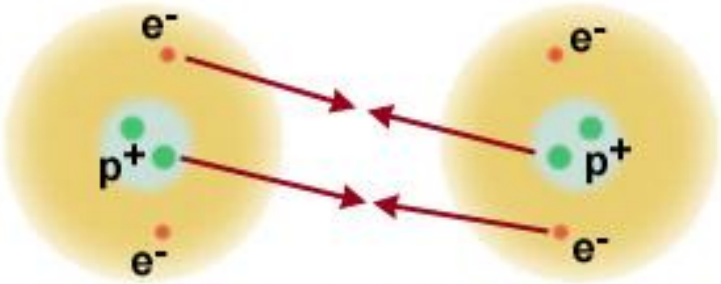
The electrical attraction is caused by the exchange of photon.

(This is finally understood by Quantum Electrodynamics)

Feynman, Schwinger, Tomonaga, 1965 Nobel Prize

How to form stable molecules from atoms?

- Since atoms are electrically neutral, what causes them to stick together to form stable molecules?
- The answer is a bit strange: an effect called the **residual electromagnetic force** allows different atoms to bind together and form molecules.



Residual E-M force in action: the atoms are electrically neutral, but the electrons in one are attracted to the protons in another, and vice versa!

Amazing, isn't it?

All the structures of the world exist simply because protons and electrons have opposite charges!

Is the Nucleus Fundamental?

- In an atom, outside of the nucleus is a cloud of negatively charged electrons (e).
- Experiments "looked" into the nucleus (and atoms) using particle probes to learn more about it.
- They discovered that the nucleus was made of

protons (p), which are positively charged,

and

neutrons (n) which have no charge.

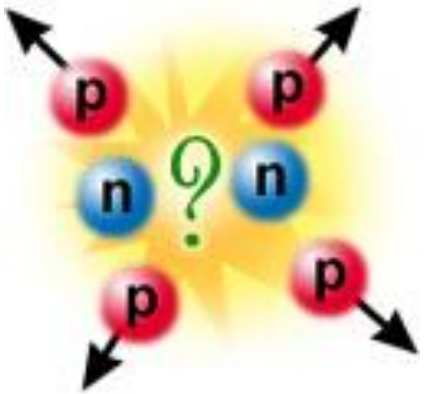
Proton Rutherford 1911; neutron Chadwick 1932

Nuclear Force hold Nucleus togethor

- Electromagnetic force hold atom together by exchanging photons.
- Similarly, Yukawa suggested:

nuclear force hold nucleus together by exchanging Pion mesons (predicted in 1935).

- Powell found charged pion in 1947.



Yukawa 1949 Nobel Prize

Botanic Garden of Particles

- Before 1937, the view of our world was simple: matter is made of proton, neutron and electron.
- By 1960's, more than 60 new particles (most of which aren't fundamental) were found: e.g.

K^0 K^+ π^0

Kaons (Rochester, Butler,1947) (Powell,1949) Neutral pion(1950)

- Physicists were trying to find any "pattern" among those newly discovered particles, similar to the invention of "Periodic Table of Elements" to organize different atoms.

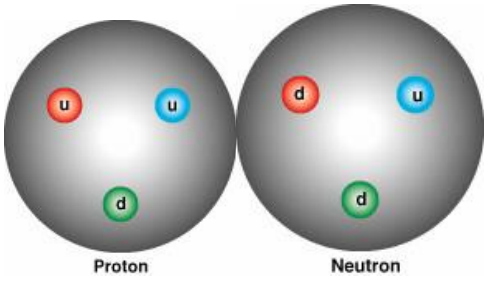
- **If a pattern exits, it implies those newly discovered particles are not fundamental.**

Are Protons and Neutrons Fundamental?

- Gell-mann found the pattern among proton, neutron pion, kion, …, called "The Eightfold Way" ("Quark Model")
- Protons and neutrons are composed of even smaller particles called **Quarks.**

Proton = (u u d) u = up quark

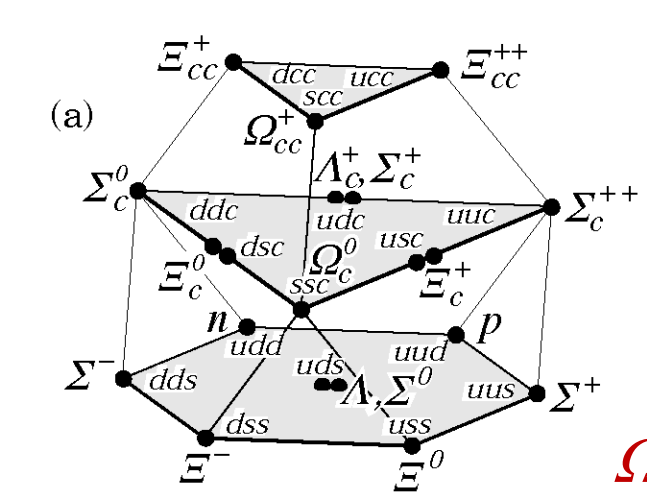
Neutron = (u d d) d = down quark

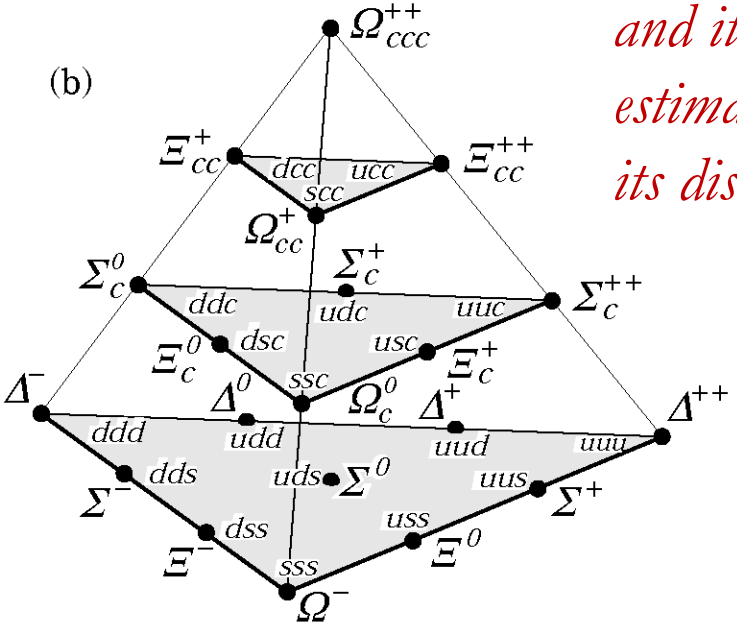


- Other particles like pion, kion, …, are also composed of quarks. (Baryon: (qqq) , Meson: ($q\bar{q}$))

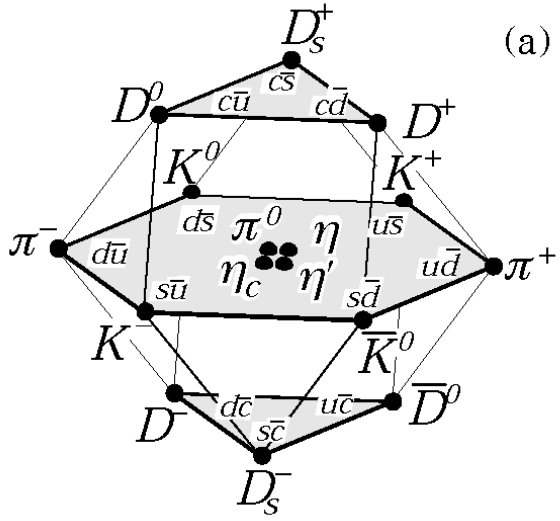
Gell-Mann, 1969 Nobel Prize

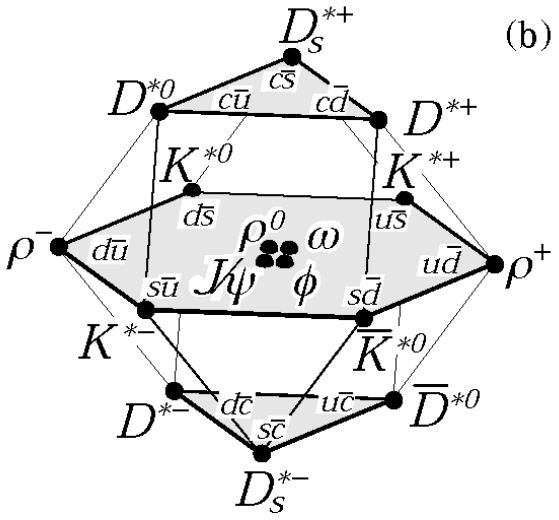
Quark Model: SU(3) Pattern among Hadrons





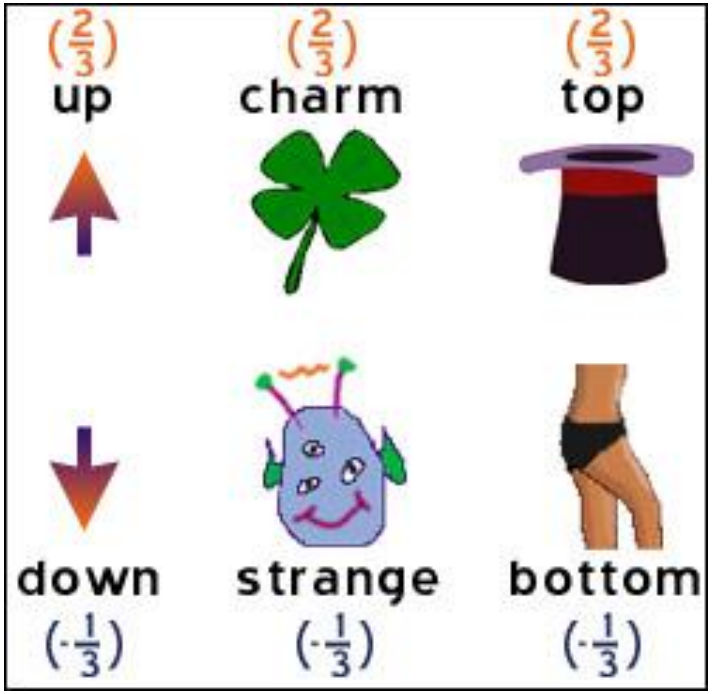
Ω was predicted and its mass was estimated prior to its discovery.





Quarks

- There are three pairs of quarks.
- The up and down are the constituents of protons and neutrons, and make up most matter.
- The other particles are produced in energetic subatomic collisions from cosmic rays or in accelerators like Fermilab.

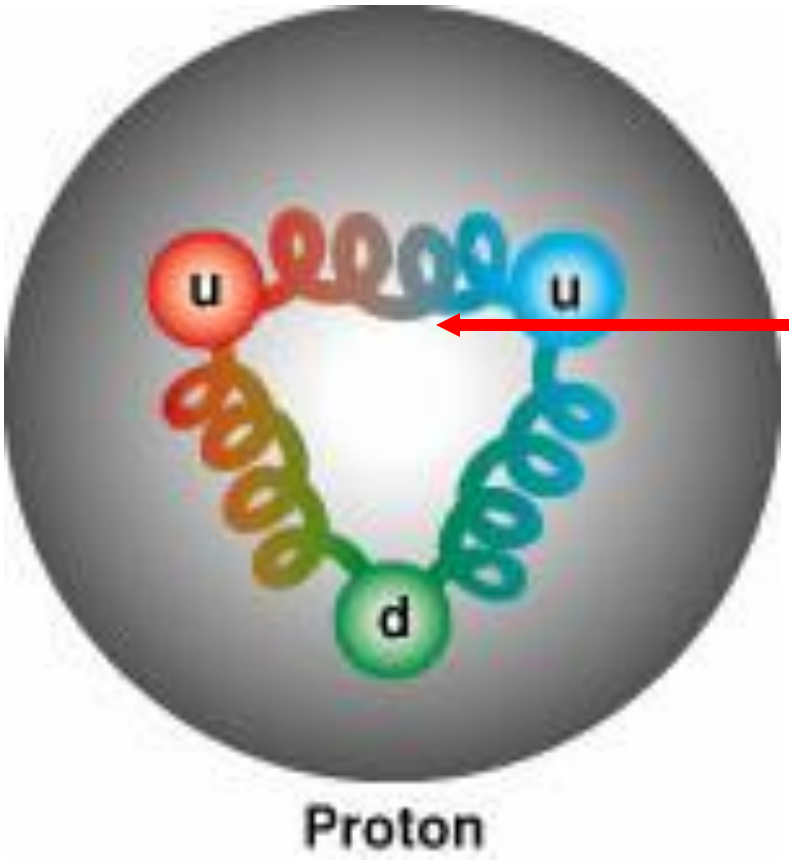


- 1974 November Revolution, Ting, Richer found charm quark.
- 1977, Lederman found bottom quark.
- 1995, Fermilab found top quark.

Gluons bind quark together

- Quarks have electric charge, and they also have another kind of charge altogether called **color charge**. The force between color-charged particles is very strong, so this force is creatively called strong force.
- The strong force holds quarks together to form hadrons, so its carrier particles are whimsically called **gluons** because they so tightly "glue" quarks together

Gluons bind quark together

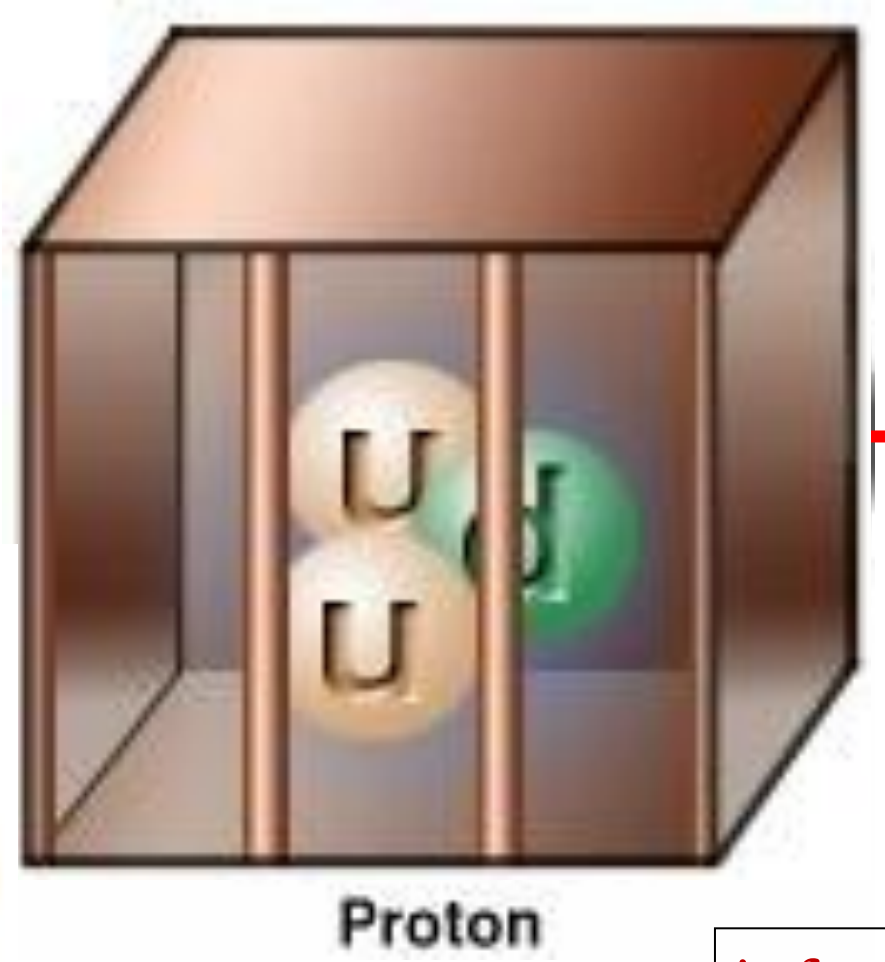


The quarks are stuck together by the exchange of gluon, which is finally understood by Quantum Chromodynamics (Asymptotic Freedom in high energy).

1973 DESY(PETRA): confirm gluon in $e^+ e^-$ ⟶ 3 jets

Gross, Wilczek, Politzer, 2004 Nobel Prize

Gluons bind quark together



In low energy, we can't see free quark. The quarks are confined inside the proton.

1 million dollars problem!

infrared confinement

The origin of nuclear force

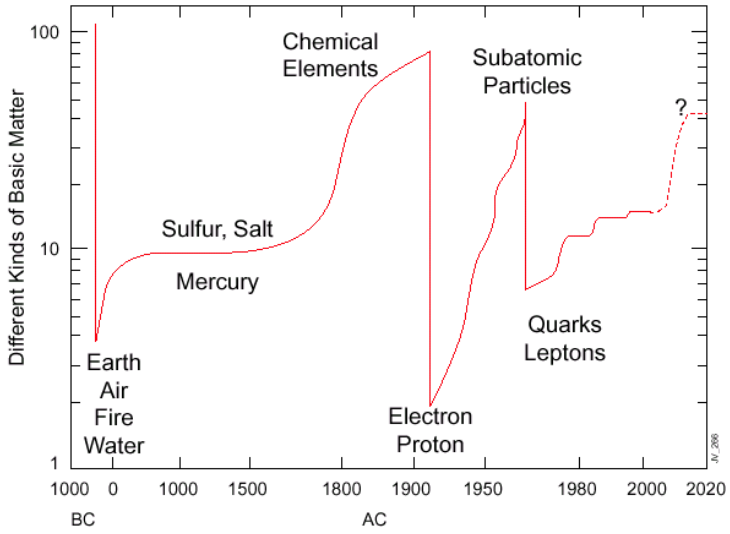
- Now back to the nucleus!
- The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively charged protons repel one another, **why doesn't the nucleus blow apart?**
- We cannot account for the nucleus staying together with just electromagnetic force. What else could there be?

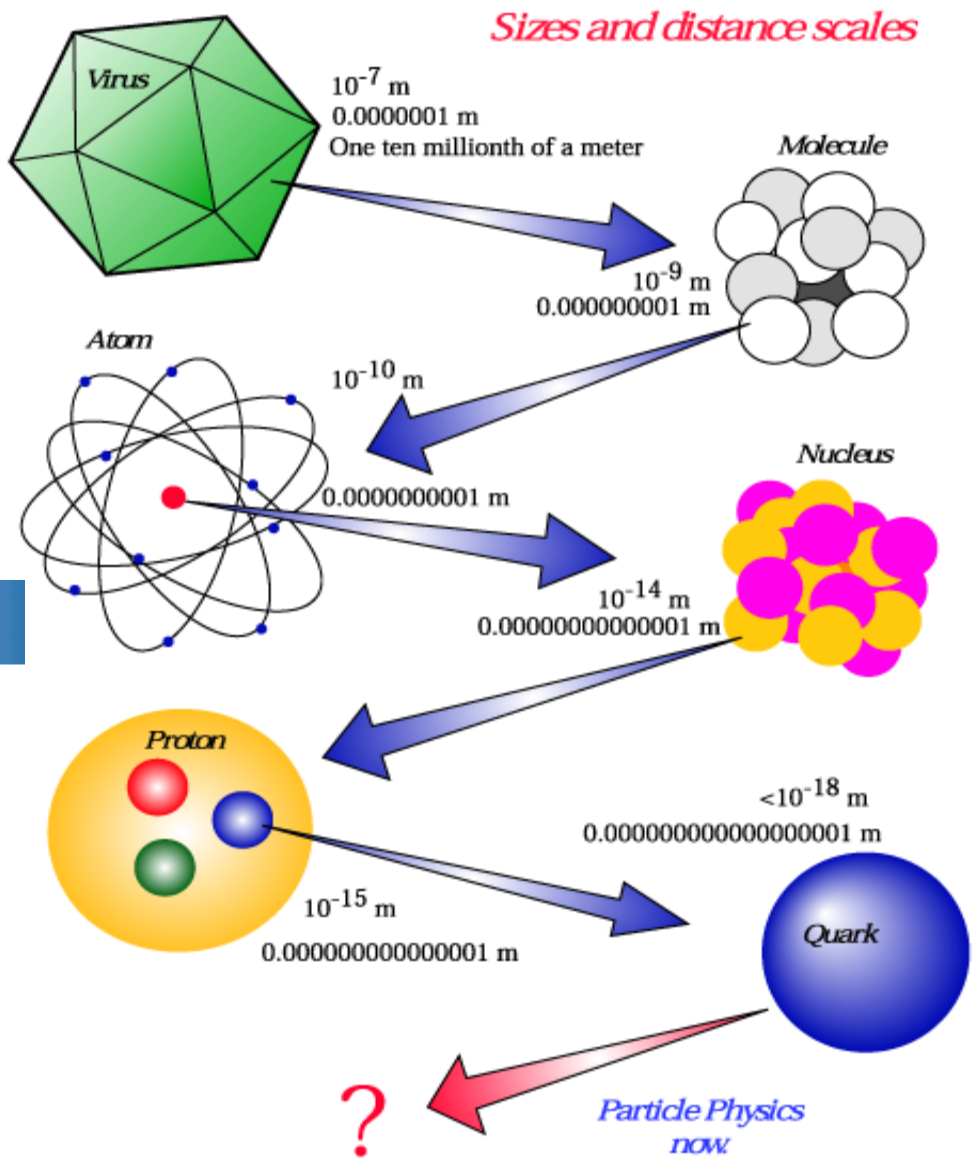
The residual strong gluon force

- While quarks have color charge, composite particles made out of quarks have **no net color charge** (they are color neutral). For this reason, strong force only takes place on the really small level of quark interactions, which is why you are not aware of strong force in your everyday life.
- The residual strong gluon force between the protons and neutrons overwhelms the repulsive electromagnetic force.
- It is what "glues" the nucleus together.

Until now, we know…

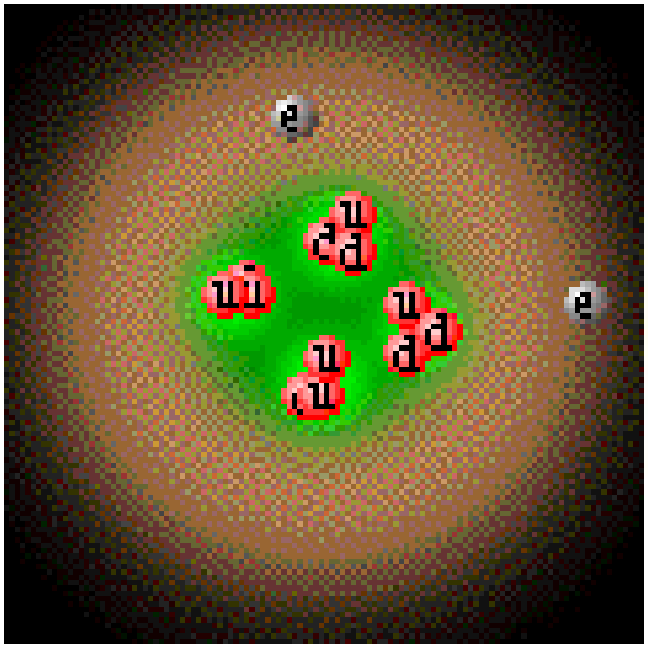
Constituents of Matter

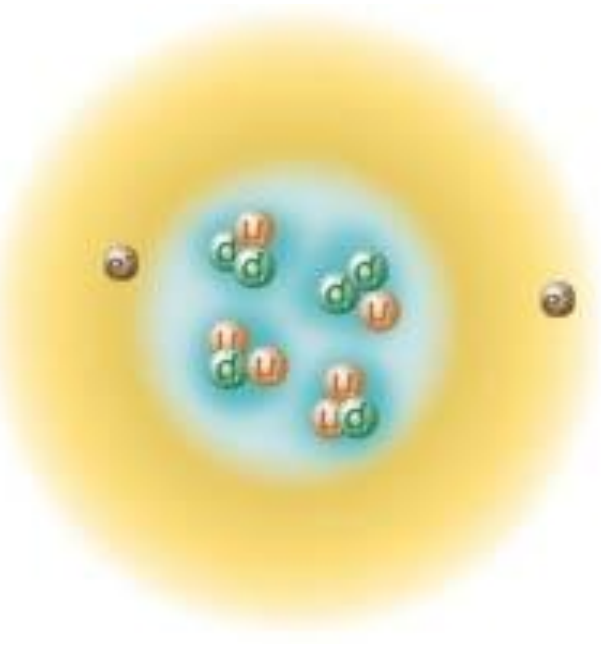




Sumarize:
The modern atom model

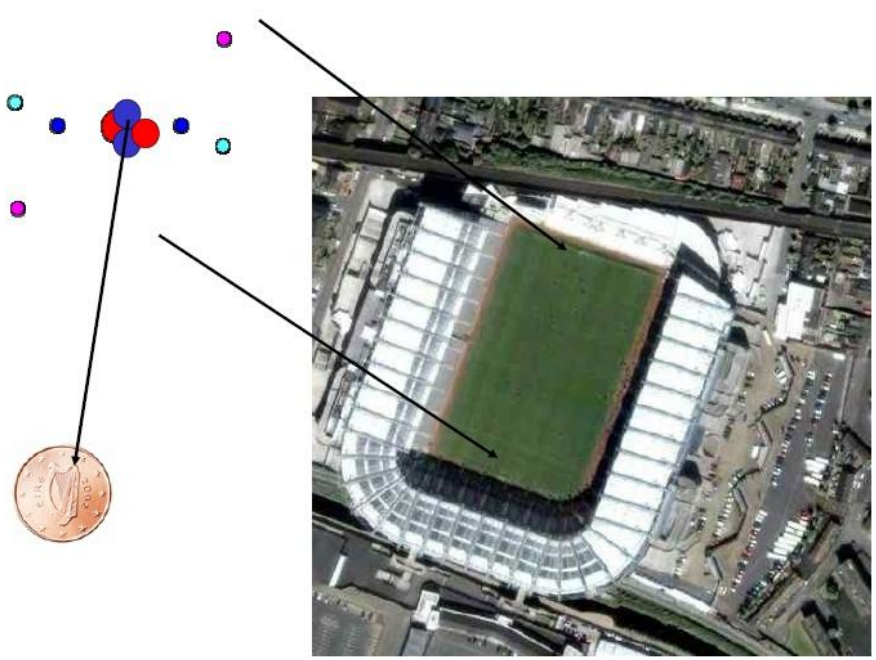
- Electrons are moving constantly around nucleus which is made of protons and neutrons which are the composites of quarks.

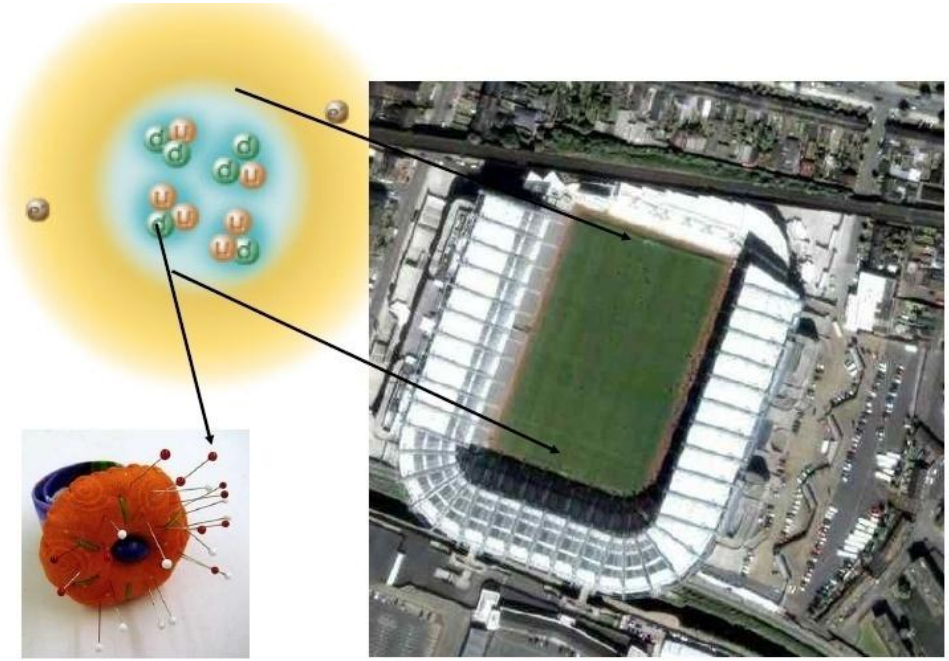




99.999999999999% of an atom's volume is just empty space!

- If we drew atom to scale and made protons and neutrons a centimeter in diameter, then electrons and quarks would be less than the diameter of hair, and the entire atom's diameter would be greater than the length of 30 football fields!

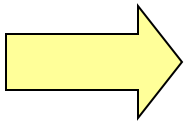




Empty Space?

- The "little universe" of atom is occupied mostly by "Emptiness".

- In fact, the 3 (u u d) quarks inside the proton only occupy one part in a billion (10^{-9}) of the proton's volume.



Lots of "Emptiness"

What is The True Nature of Emptiness?

Interactions Generate Mass

- Quarks themselves only contribute a very small part, about 1.3%, of the proton (uud) mass:

- 99.7% of proton mass originates from the interactions among the 3 quarks inside proton. (Mass is a form of kinetic and potential energy.)

Nambu (Nobel Prize 2008)

- These energies are converted into the mass of the proton as described by Einstein's equation that relates

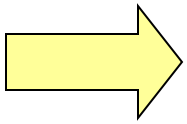
Energy (E) to Mass (M) by

$$E = M c^2$$

C is the speed of light = 3×10^8 meters per second.

The Emptiness inside a Proton

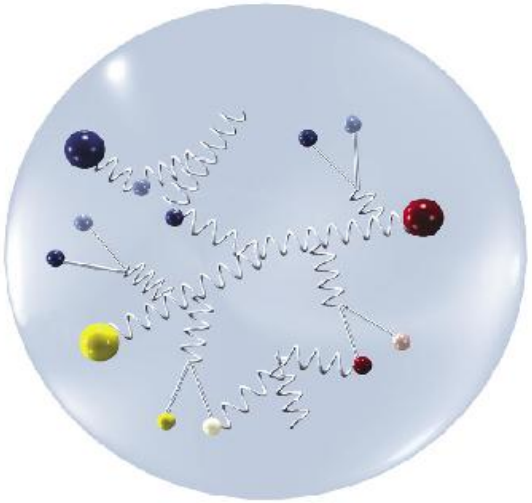
- More than 99.9999999% of the proton's volume is empty space!
- The mass of proton is mainly generated by the contribution from the empty space (Emptiness) inside the proton.



"Emptiness" is not "void".

Mass is a form of Energy.

The Modern Proton



The Proton

Mostly a very dynamic self-interacting field of gluons, with three quarks embedded.

Like plums in a pudding.

- 99% of the proton's mass/energy is due to this self-generating gluon field
- The two u-quarks and single d-quark
  - 1. Act as boundary conditions on the field (a more accurate view than generators of the field)
  - 2. Determine the electromagnetic properties of the proton
    - *Gluons are electrically neutral, so they can't affect electromagnetic properties*
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Has nothing to do with the quarks

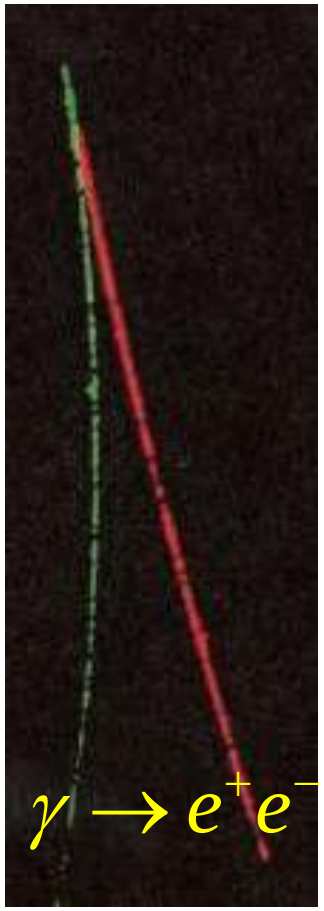
The key point is

Antimatter

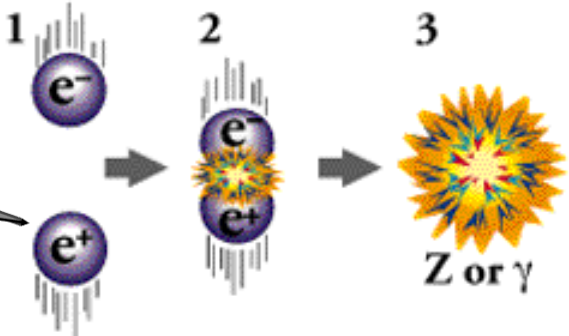
- Dirac's theory of electron (1920's), consistent with Quantum Mechanics and Einstein's Special Theory of Relativity, predicts that:

➢ For every type of matter particle we've found, there also exists a corresponding antimatter particle, or **antiparticle**.

➢ Pure energy can create a pair of particle and antiparticle.



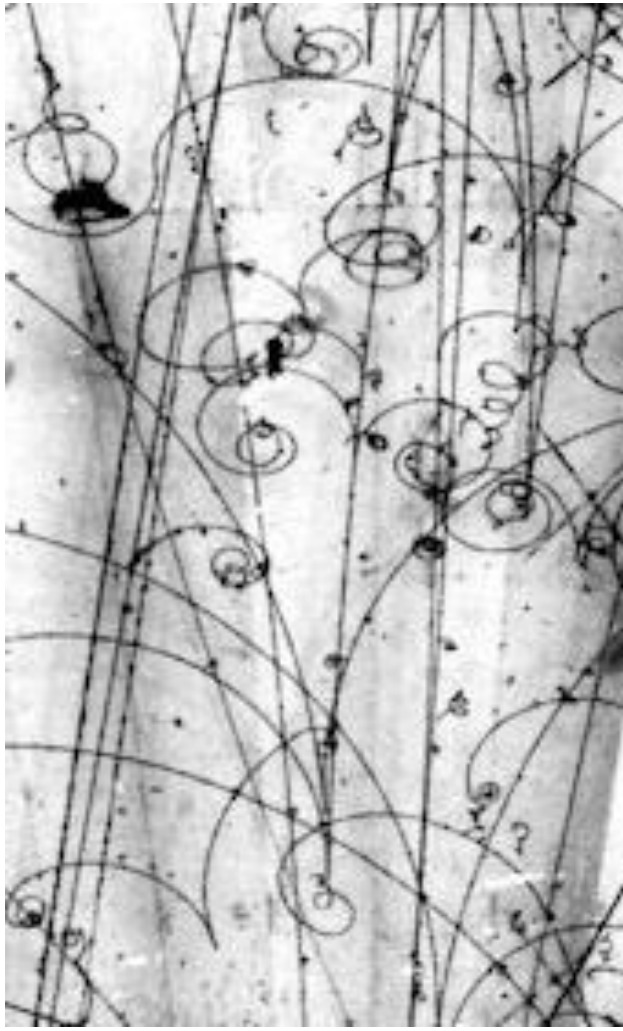
➢ When a matter particle and antimatter particle meet. they annihilate into pure energy!



Evidence for anti-matter

- This is a bubble chamber photo
- There is a collision of a proton into a target. The bubble chamber is in a magnetic field.
- Can you spot the anti-matter?
  - The magnetic field makes negative particles curl one way and positive particles the other.
  - Positrons (anti-electrons) behave just like the electrons but curl in the opposite way

    because they have the opposite charge.
  - Electron-positron pairs appear as if from nowhere, but are in fact from photons, which don't leave a trail.



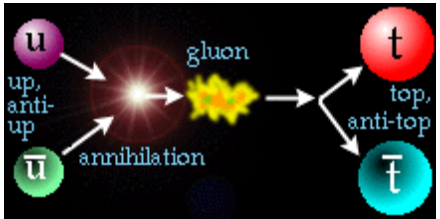
CARL D. ANDERSON

The production and properties of positrons

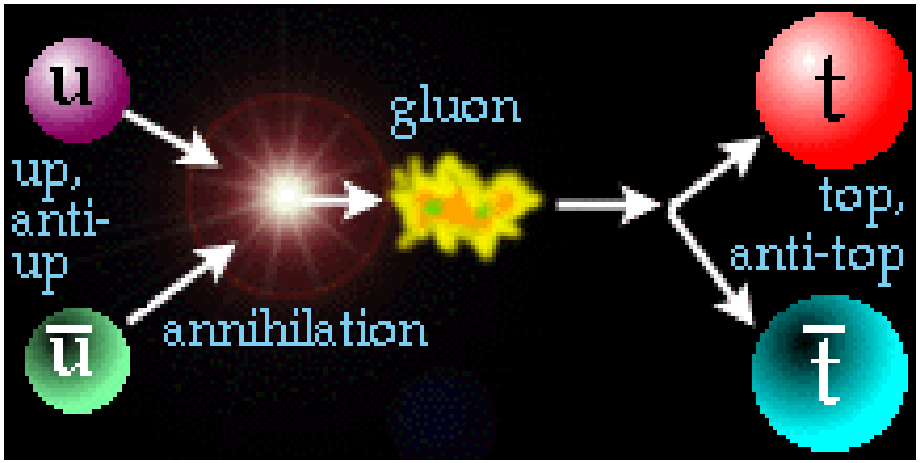
Nobel Lecture, December 12, 1936

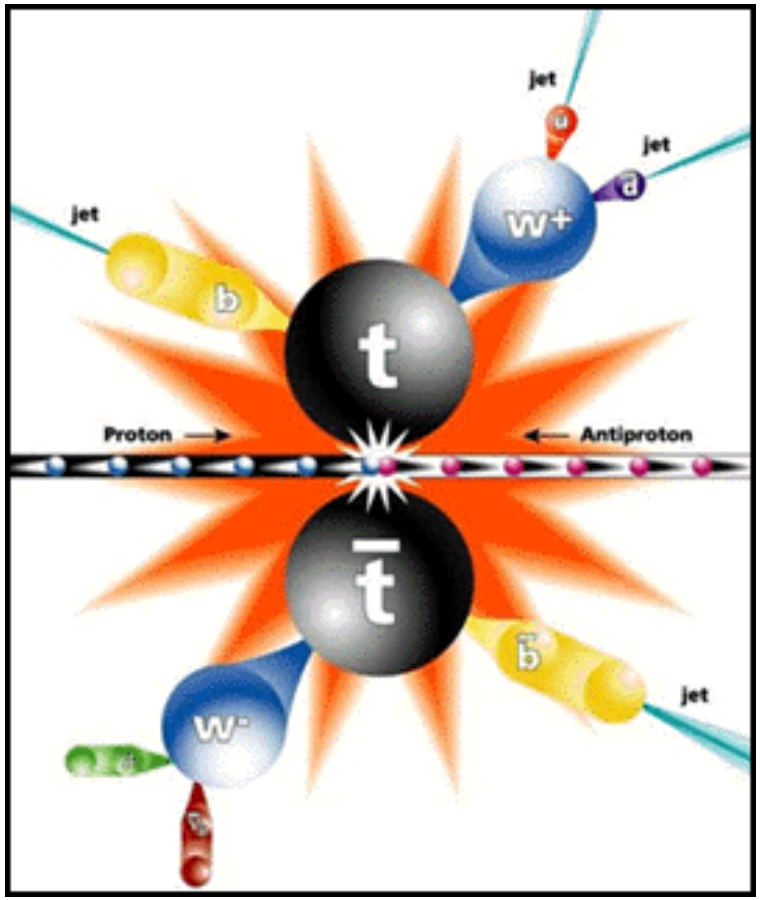
Annihilation

- In an annihilation, a matter and an antimatter particle completely annihilate into energy.
- During an annihilation, a matter and antimatter particle interact with each other, converting the energy of their previous existence into a very energetic force carrier particle (a gluon, W/Z, or photon). These force carriers, in turn, are transformed into other particles.
- This is what we did at Fermilab, USA -- annihilate two particles at tremendous energies in order to create new, massive particles.



Top Quark and Anti-Top Quark Pair Production at Hadron Collider





Discovered in 1995 at Fermilab

Fermilab Tevatron Collider

- Collide protons and anti-protons at CDF and D0
- Total energy is 1.96×10^{12} eV
- Circumference is 6.28 km
- Top quark was discovered here in 1995
- Tau neutrino was discovered here in 2000

“Beam me up Scotty!”

- **"Antimatter?" "Pure energy?"**

What is this, *Star Trek?*

- The idea of antimatter is strange, made all the stranger because the universe appears to be composed entirely of matter. Antimatter seems to go against everything you know about the universe.
  - What happens if you put anti-coffee into a coffee cup?

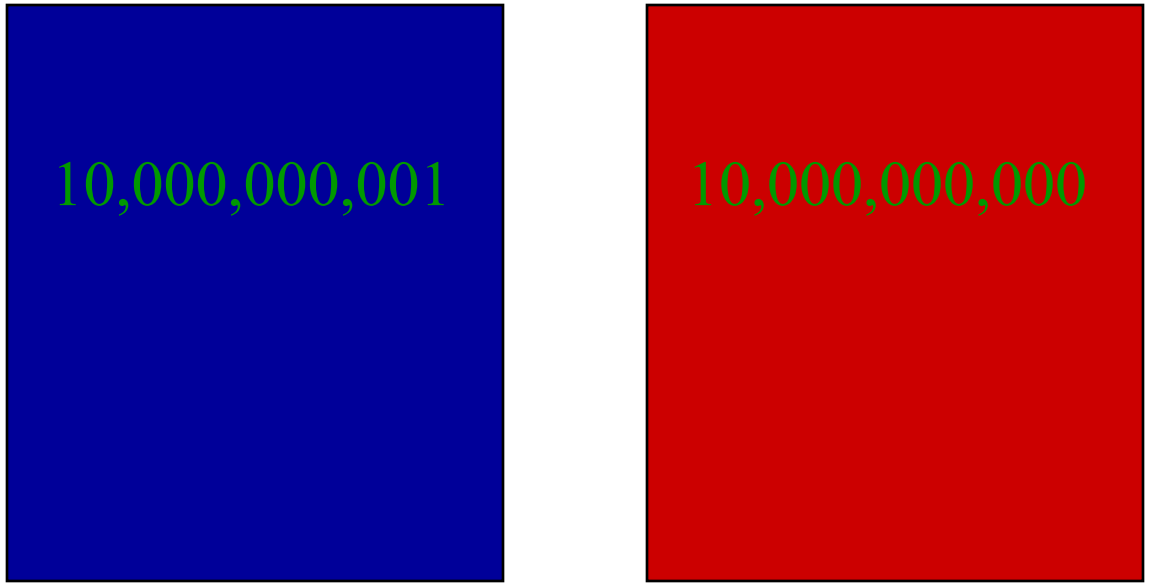
  If antimatter and matter are exactly equal, but opposite in electric charge, then why is there so much more matter in the universe than antimatter?

  This is one of the “million dollar questions!”

Matter and Anti-Matter

Where did anti-matter go?

Matter and Anti-Matter in Early Universe



Matter and Anti-Matter in Current Universe

us

1

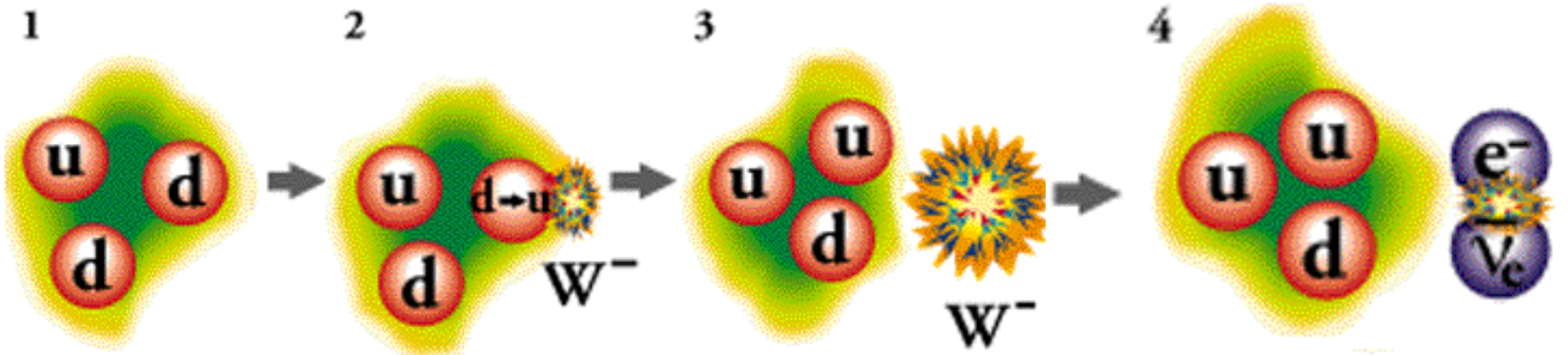
Matter Anti-matter

The Great Annihilation

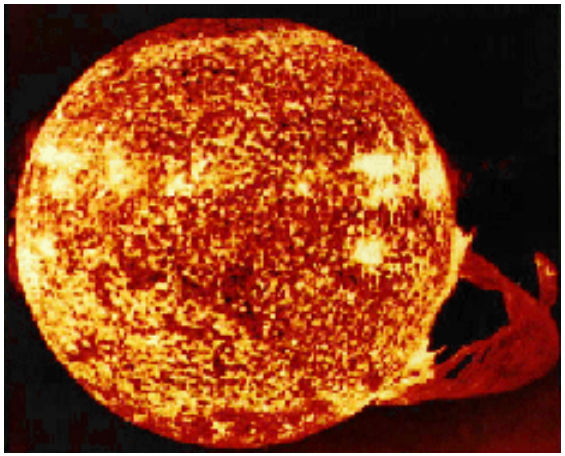
I think I finally understand atoms

Nothing lasts for ever

The (free) neutron is radioactive and decays after 15 minutes into proton, electron and "neutrino" (electron-like neutral particle)

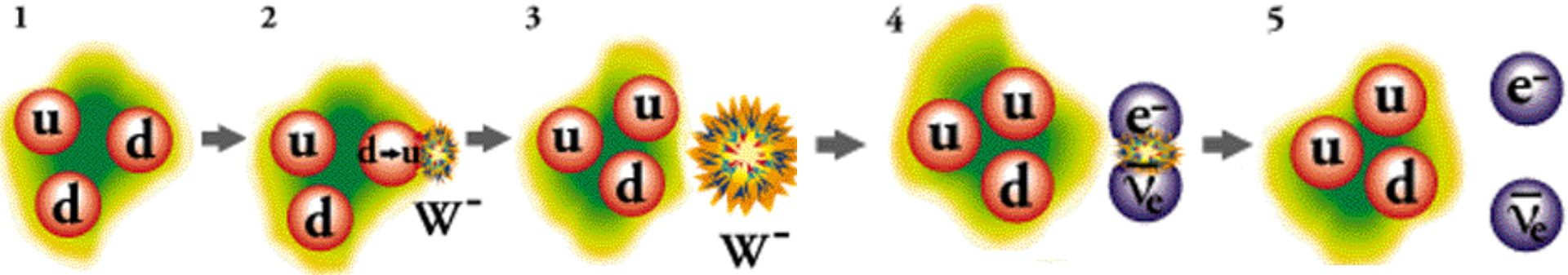


This decay process is very weak (15 minutes is an eternity!) Without such weak interactions the Sun would not shine!



The Weak Force

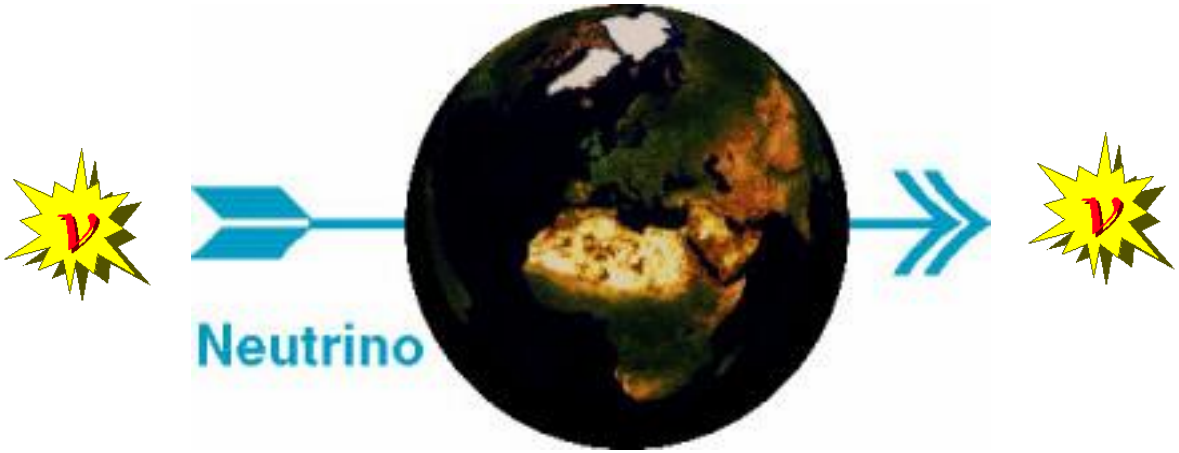
- At the quark level, a down quark in the neutron decays into an up quark, by emitting a W boson.
- The heavy W boson is the carrier of the weak force.
- Since the W is very heavy (more than 80 times the proton itself), it takes a long time for quantum fluctuations to gather the where-with-all to support the decay. Thus a "weak" decay.
- Finally the W itself decays into leptons



Neutrinos from the Sun

Question: How many neutrinos from the Sun are passing through your fingernail in one second?

Answer: 40 billion! – day and night since neutrinos can pass right through the Earth without interacting



(1956 Cowan, Reines)

predicted by Pauli, 1933

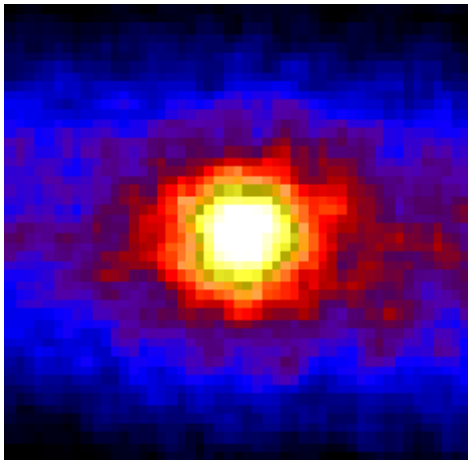
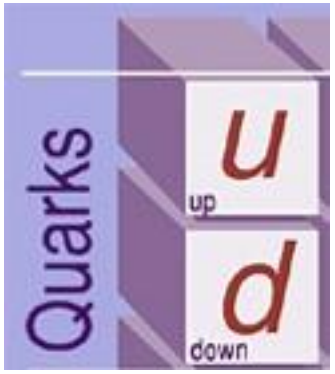


Photo of Sun taken underground using neutrinos

W particles – the left-handed alchemists



W^-

Just like rifle bullets, quarks and leptons spin as they whizz along

W^+

The quarks and leptons can only see W particles if they spin to the left!

This shatters mirror symmetry!

(Lee and Yang, Nobel prize 1957)

Electroweak theory predicted a heavy version of the photon called Z^0 which was discovered in 1983 (Rubbia, van der Meer)

Until now, we know

- The Elementary Constituents of Matter.

AND

- The forces that control their behaviour at the most basic level.

Interactions

Four forces in Nature

1 Gravity

Newton

2 Electromagnetism

Faraday

3 Weak Interaction

Beta (radioactive) decay

Muon decay

Time scales: $10^{-12} \sim 10^{3}$ sec

4 Strong Interaction

Hold nuclei together

Particle collision

Time scales: 10^{-23} sec

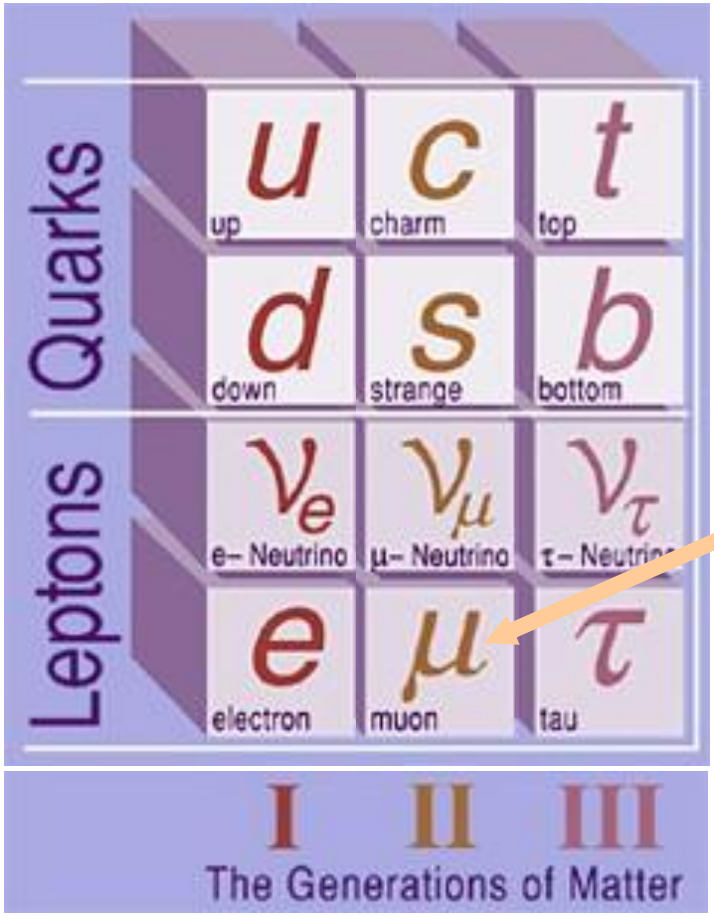
Quarks

- Elementary particle (a point-like particle; can be much heavier than a composite particle, such as proton; e.g., top quark mass is 173 times of proton mass.)
- Involved in strong, weak and electromagnetic interactions

Leptons

- Elementary particle (a point-like particle)
- Not involved in strong interaction

Quarks and Leptons



Why 3 families?

The introduction of electron neutrino

- The (elctron) neutrino was postulated first by Pauli in 1930 to explain how beta decay could conserve energy, momentum, and angular momentum (spin).
- In contrast to Bohr, who proposed a statistical version of the conservation laws to explain the observed continuous energy spectra in beta decay.
- Fermi named this "little neutral one“ particle as neutrino.

Electron and its neutrino

The electron was discovered in 1897, by Joseph Thomson.

The electron's anti-particle, positron, was predicted by Paul Dirac in 1928, and discovered by Carl Anderson in 1932.

From Zhi-zhong Xing's Neutrino physics lectures

In 1956 Clyde Cowan and Frederick Reines discovered the positron's partner, electron antineutrino.

Muon

The muon particle, a sister of the electron, was discovered in 1936 by Carl Anderson and his first student S. Neddermeyer; and independently by J. Street *et al.*

It was not Hideki Yukawa's "pion". And it was the first flavor puzzle.

Isidor Rabi famously asked:

Who ordered that?

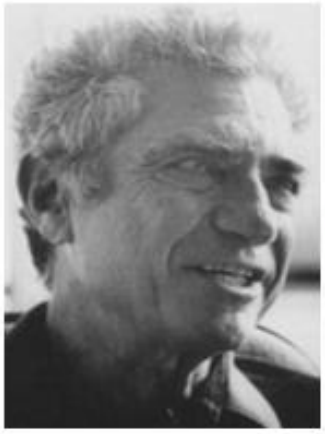
Isidor Isaac Rabi

FAMILY

Muon neutrino

The muon neutrino, the muon's neutral counterpart, was discovered by Leon Lederman, Melvin Schwartz and Jack Steinberger in 1962.





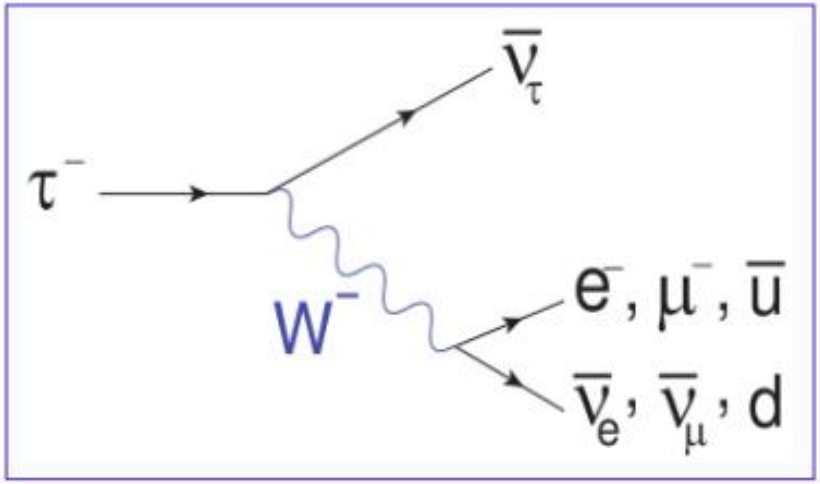

Neutrino flavor conversion was proposed by Z. Maki, M. Nakagawa and S. Sakata in 1962.

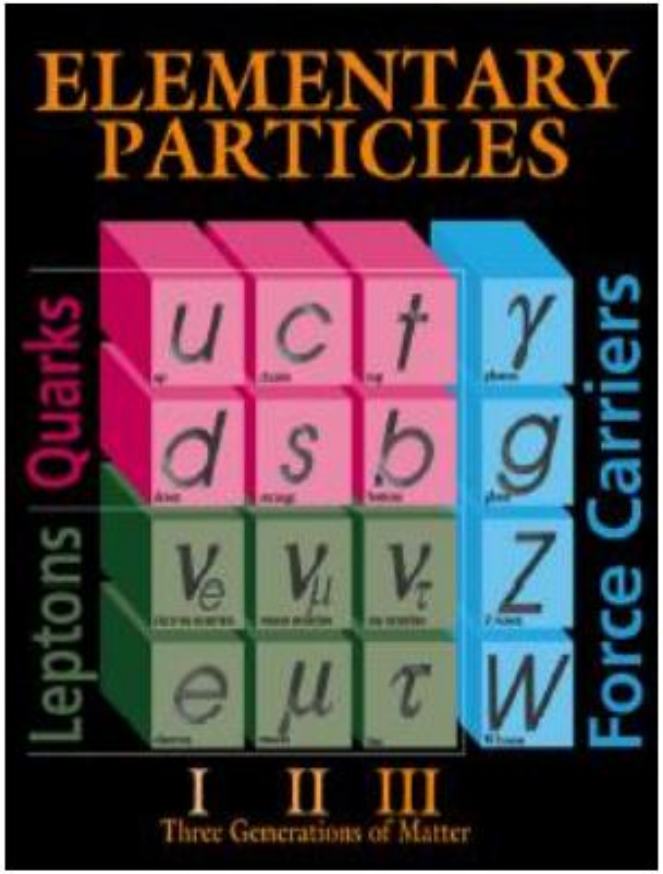
Neutrinos convert into antineutrinos first proposed by Bruno Pontecorvo in 1957.

Tau and its neutrino

The tau particle was discovered by Martin Perl in 1975 via:

$$e^+ + e^- \rightarrow e^{\pm} + \mu^{\mp} + \text{undetected particles}$$





In 2000, the tau neutrino was finally discovered at the Fermilab.

The lepton family is complete!

Leptons and Nobel Prizes

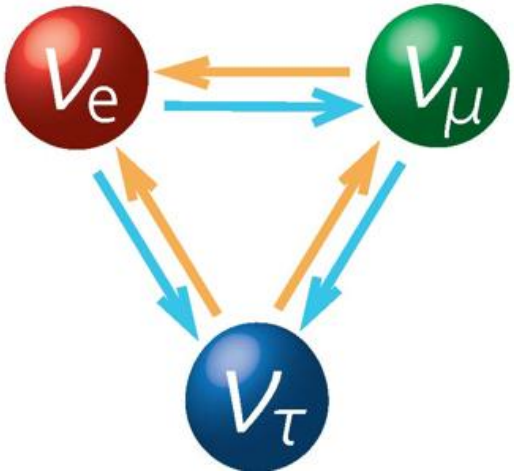
e	J.J. Thomson 1897	J.J. Thomson 1906 (NP)
ν_e	C.L. Cowan et al. 1956	F.J. Reines 1995 (NP)
μ	J.C. Street et al. C.D. Anderson 1936	1975 – 1936 = 1936 – 1897 = 39
ν_μ	G. Danby et al. 1962	M. Schwartz, L.M. Lederman, J. Steinberger 1988 (NP)
τ	M.L. Perl et al. 1975	M.L. Perl 1995 (NP)
ν_τ	K. Kodama et al. 2000	

Antimatter: Positron.

Predicted by P.A.M. Dirac in 1928.
Discovered by C.D. Anderson in 1932; Nobel Prize in 1936.

Neutrino Oscillations (2015 Nobel Prize)

Due to neutrino masses, whose generation mechanism is sensitive to New Physics.



Takaaki Kajita

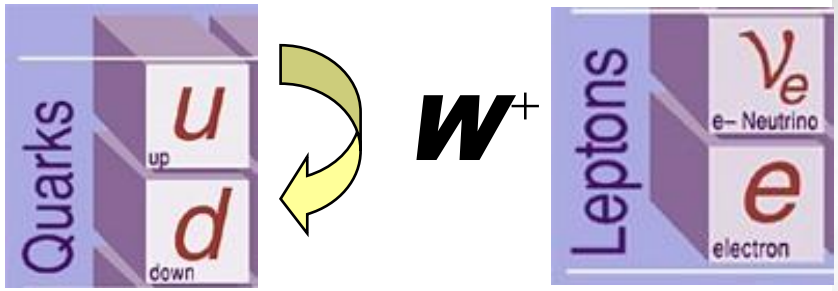
Arthur B. McDonald

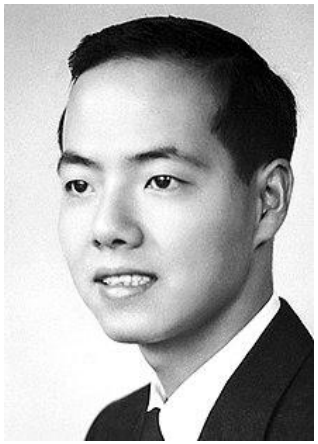
(In 1968, neutrino masses were assumed to be zero.)

The Weak Force

The Weak Force

- Parity Violation





(Lee and Yang, Nobel prize 1957)

Chien-Shiung Wu

- The unified weak and electromagnetic interaction

(Glashow, Salam and Weinberg, Nobel prize 1979)

The Sun and the W boson mass

- The Sun is powered by the nuclear fusion

$$4\,p \rightarrow {}^{4}He + 2\,e^{-} + 2\,\bar{\nu}_e + 26.73\ \text{MeV}$$

- It's a Weak interaction – carried by the W boson.
- The Sun can shine for billions of years – it's because W boson is heavy, about 80 times of proton mass.
- Why is the W boson so heavy?

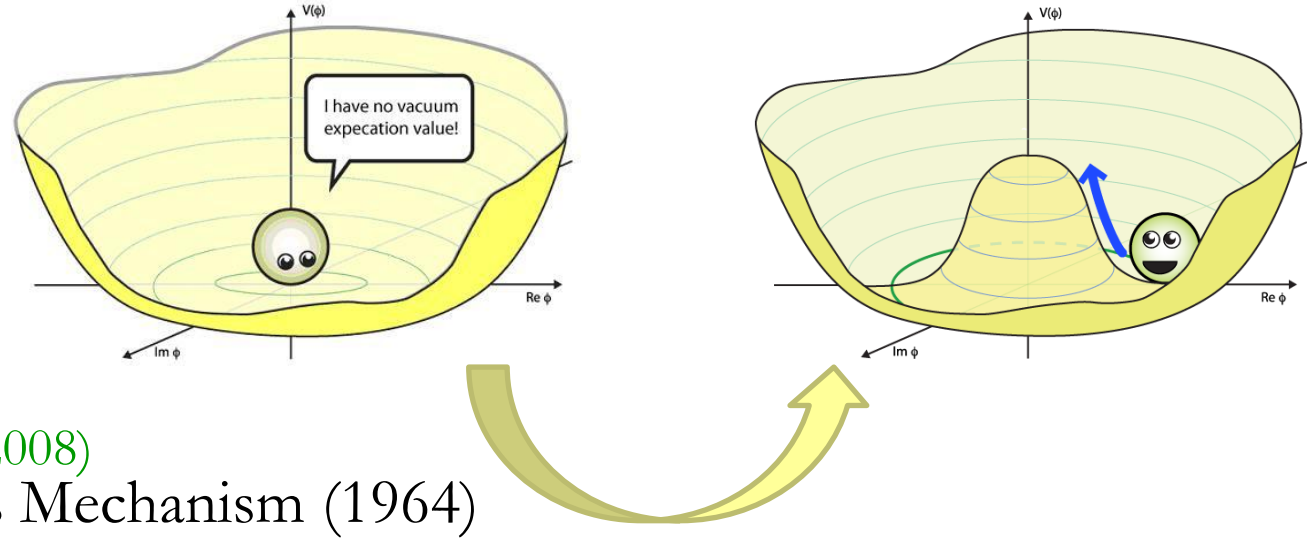
Higgs mechanism

Brout-Englert-Higgs Mechanism

(Generate mass for W and Z Bosons)

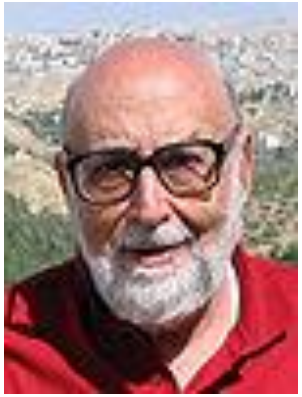
- Spontaneously broken symmetry

Nambu (Nobel Prize 2008)



- Brout-Englert-Higgs Mechanism (1964)

Brout



Englert

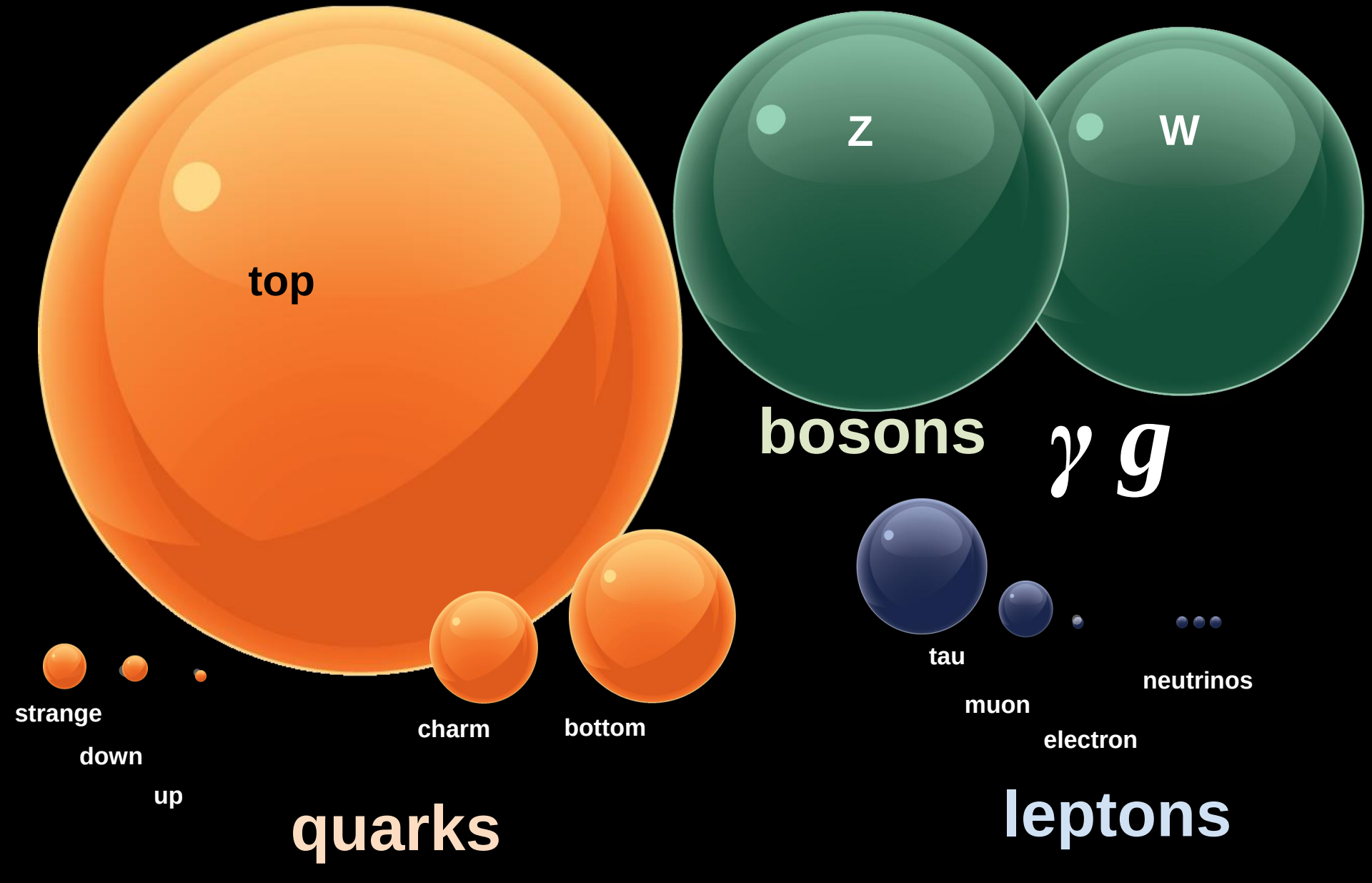
Peter Higgs

Englert, Higgs
2013 Nobel Prize

W and Z boson masses

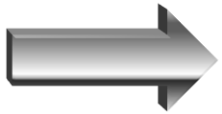
- W and Z boson masses were predicted by the Standard Model of particle physics to be about 80 and 91 GeV in 1968
- They were discovered in 1983 at CERN.
- Nobel prizes, Rubbia and van der Meer, 1984.

How do they gain Mass?

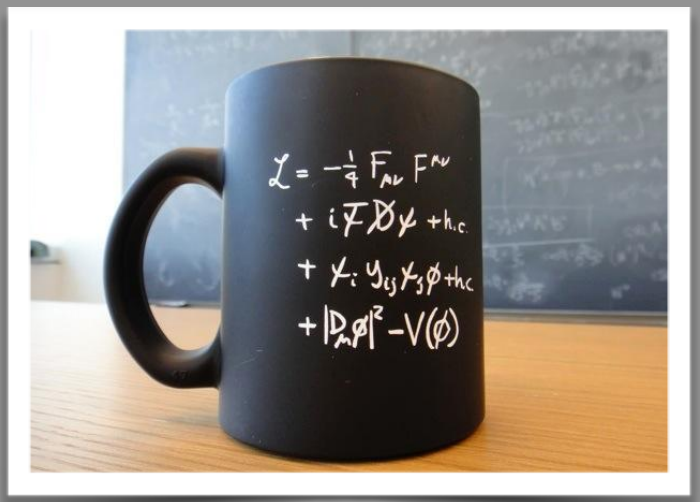


Higgs Boson generate the mass of ALL massive particles in the Standard Model.

- W and Z gauge bosons
- Higgs boson
- All (Dirac) Fermions: 6 quarks and 6 leptons
- If neutrinos are found to be their own anti-particles, i.e. Majorana fermions,



New Physics beyond the Standard Model is required.



+

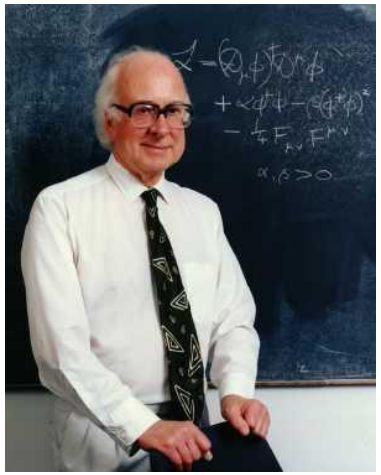
=

Higgs Mechanism

Gauge principles

Standard Model

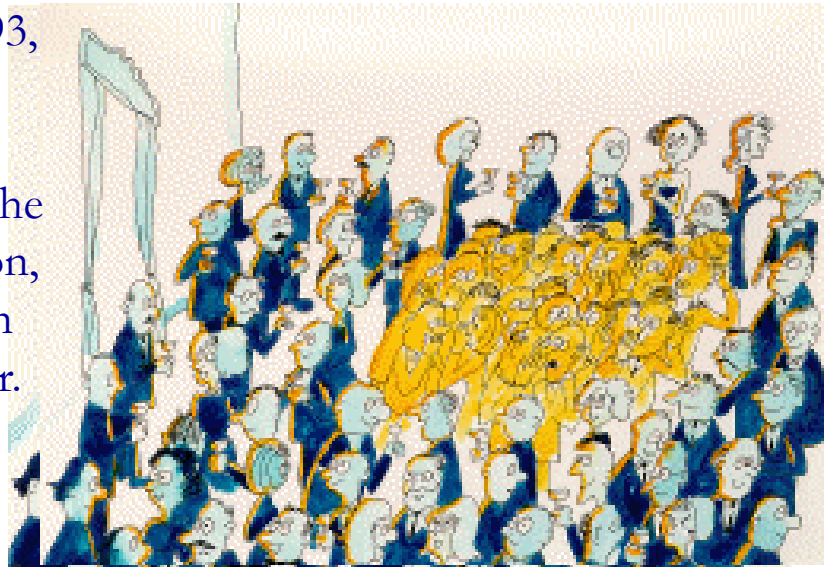
The Higgs Boson

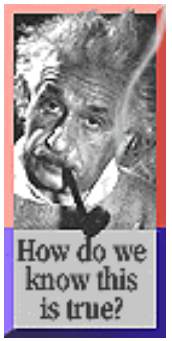


In the "Standard Model" the origin of mass is addressed using a mechanism named after the British physicist Peter Higgs.

This predicts a new particle: the Higgs boson.

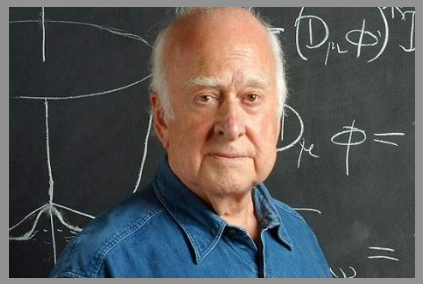
What is the Higgs boson? In 1993, the then UK Science Minister, William Waldegrave, issued a challenge to physicists to answer the questions 'What is the Higgs boson, and why do we want to find it?' on one side of a single sheet of paper. This cartoon is based on David Millar's winning entry.



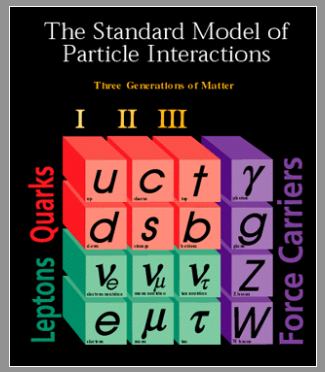


The Search for the Higgs Boson

1964: Higgs boson was hypothesized



1967: The Standard Model was born



1989: Large Electron-Positron Collider

2001: Fermilab Tevatron

2010: The Large Hadron Collider started taking data

2012: Something was discovered!

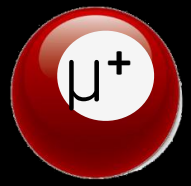
On Mass Resonances

$$m = \frac{E}{c^2}$$

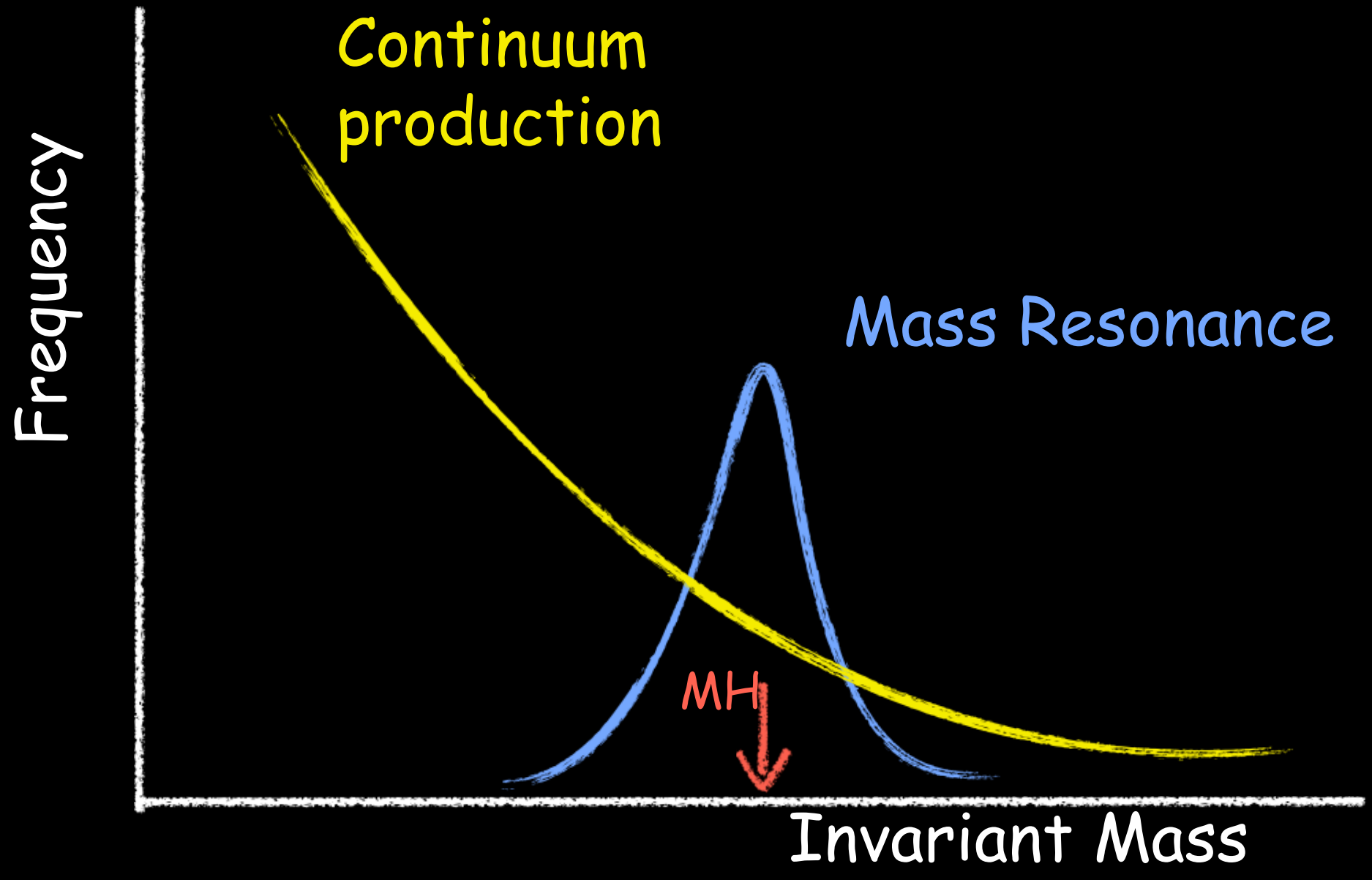
$$m = \frac{E}{c^2}$$

$$m = \frac{E}{c^2}$$

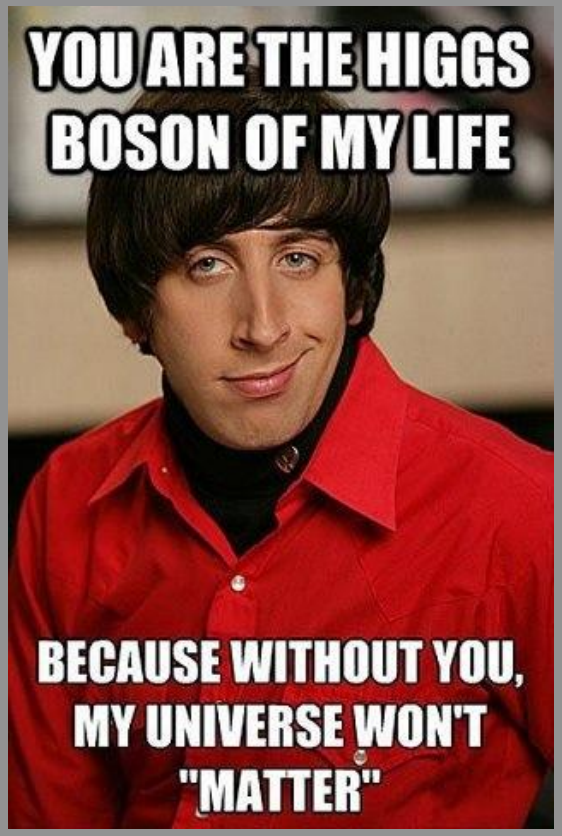
$$m = \frac{E}{c^2}$$

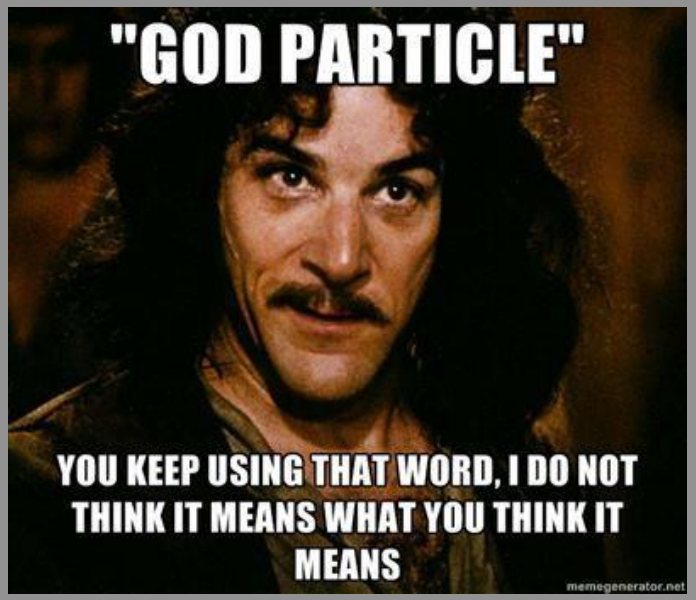


$$H \rightarrow$$
$$Z^0(\rightarrow \mu^- \mu^+)$$
$$Z^0(\rightarrow e^- e^+)$$


Continuum
production
Mass Resonance
MH
Frequency
Invariant Mass

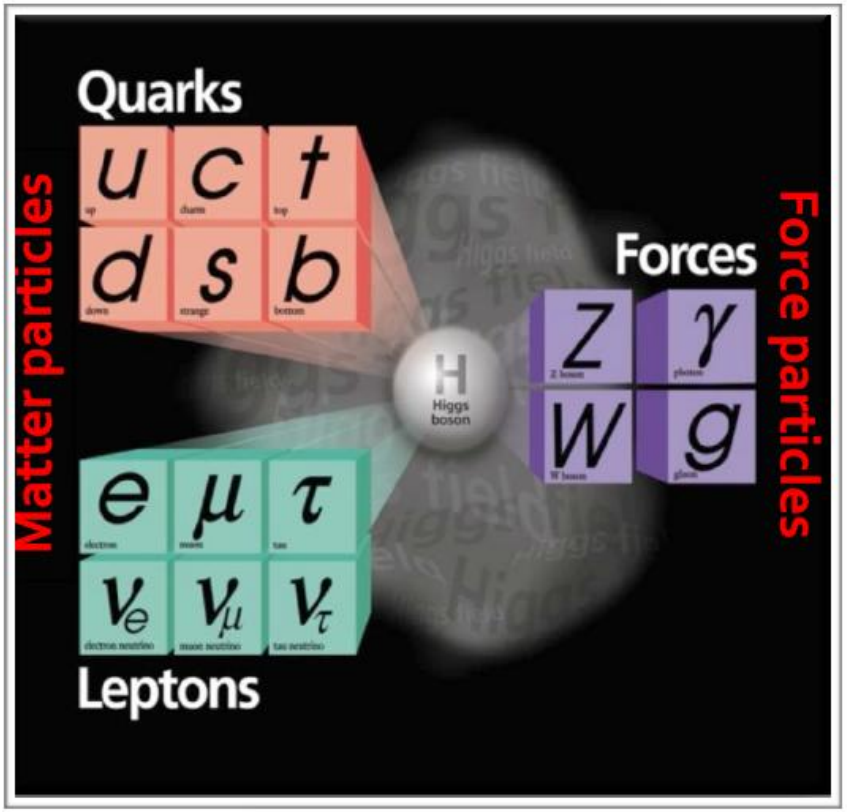
A Cultural Reaction!



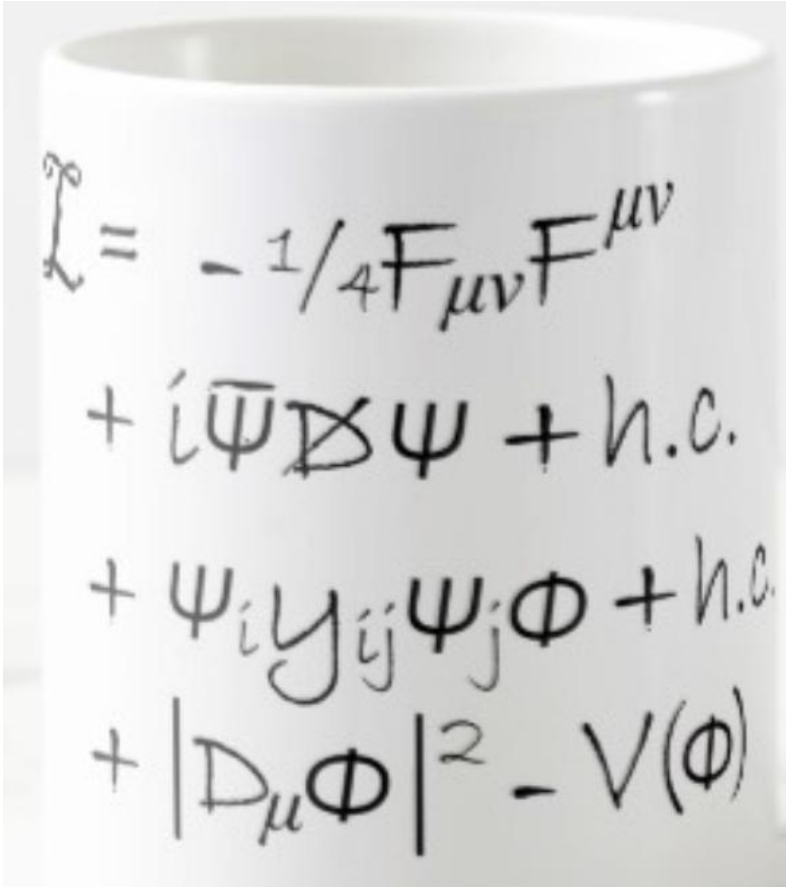


The Standard Model of Elementary Particle Physics

Simplicity and Beauty of The Standard Model

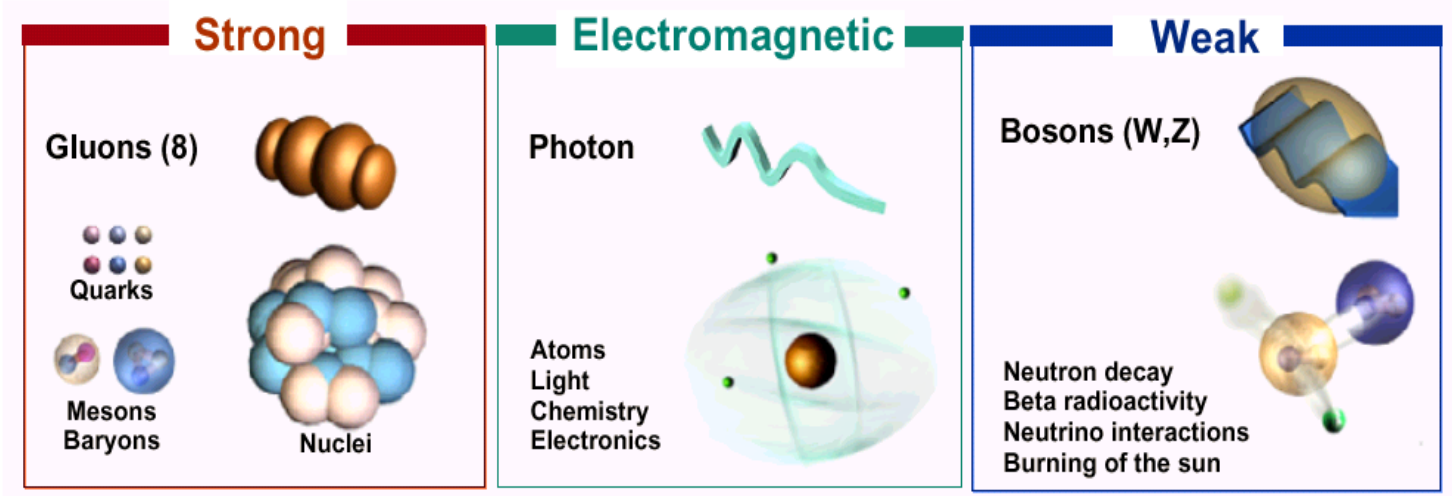


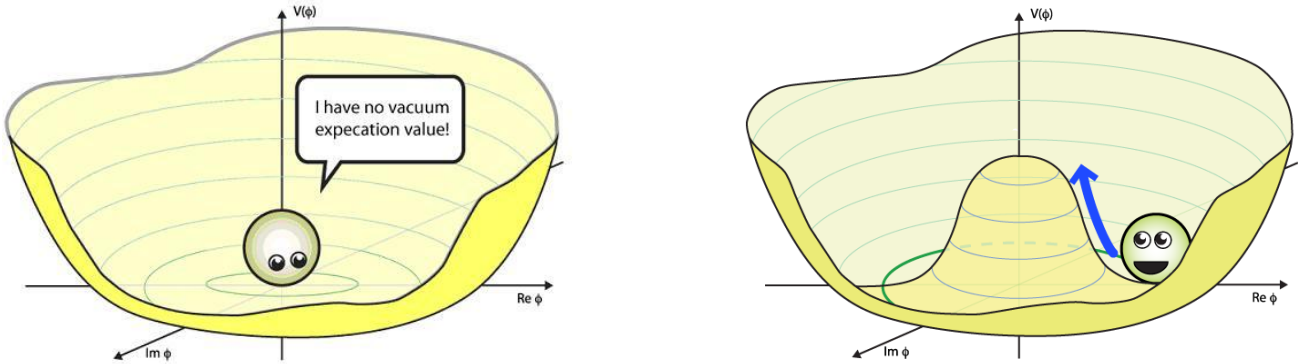
Periodic Table of Elementary Particles



SM Lagrangian

The Standard Model of Particle Physics

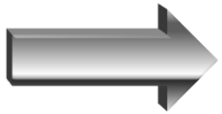




Brout-Englert-Higgs Mechanism

Importance of Higgs mass generation

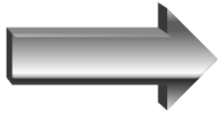
- $m_u \sim 2.2$ MeV, and $m_d \sim 4.7$ MeV; generated by Higgs mechanism.
- If $m_u = m_d$, and assume the proton were electrically charged neutral, then $m_p = m_n$, because proton (and netron) mass (about 940 MeV) is dominated by QCD interaction to bound quarks together.
- If $m_u = m_d$, then $m_p > m_n$, because proton is electrically charged.

   Our universe (including us) will not exist.
- $m_n - m_p \sim 1.3$ MeV is crucial to the formation of all elements in the periodic table.

Importance of Higgs mass generation

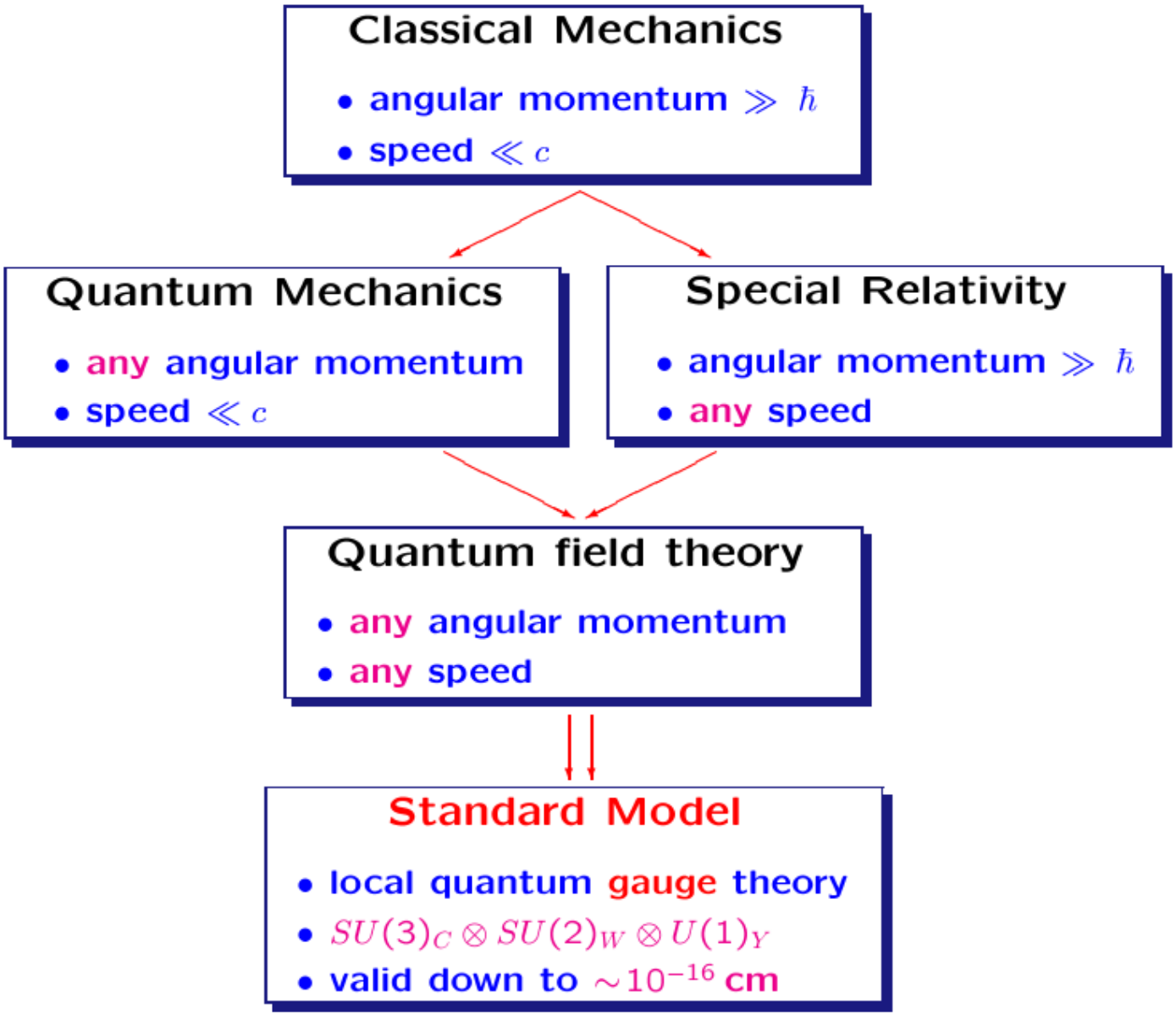
- If electron mass were not 0.511 MeV, the energy levels of Hydrogen atom (in Bohr model) will not be

$$E_n = \frac{-13.6\ \text{eV}}{n^2}$$

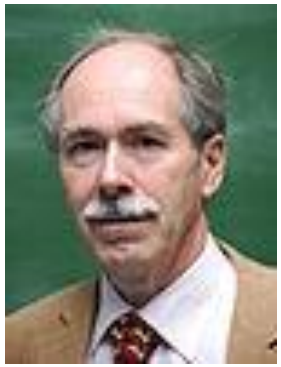
 Photosynthesis will not occur, and we will not exist.

- Or, it would be a completely different universe.

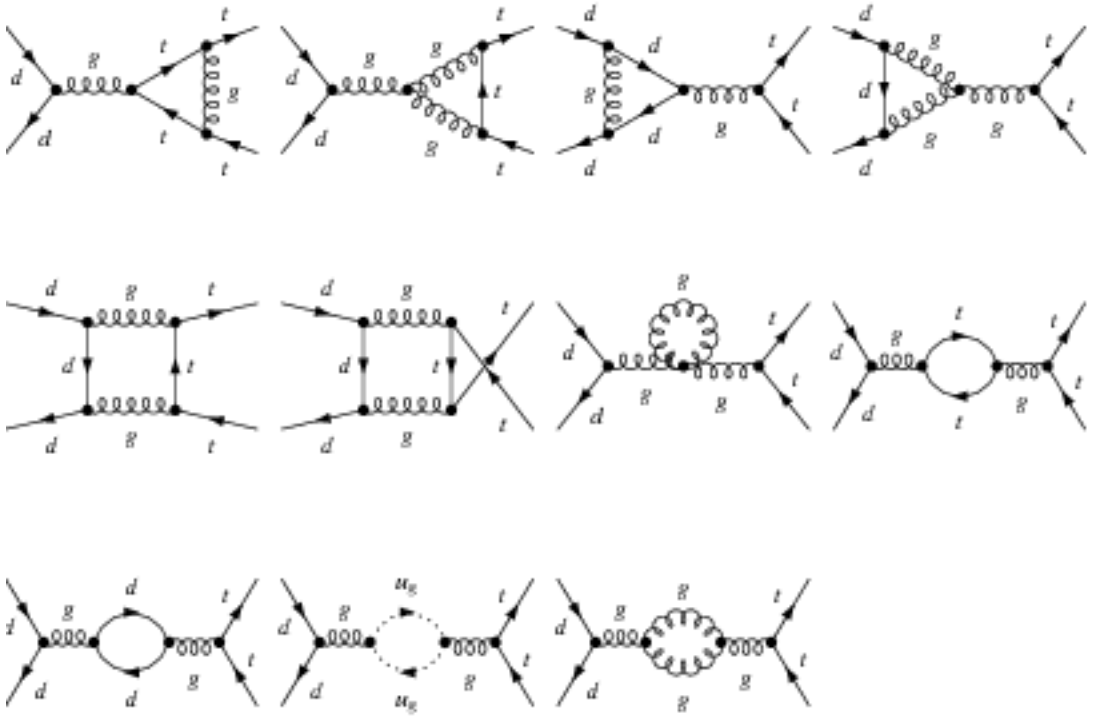
Shape of the Standard Model



The *Renormalization and Loop calculation* (Renormalizable Theory)



't Hooft, Veltman, 1999 Nobel Prize



They showed us how to perform precision calculations for quantum field theories in order to compare with experimental data – to test the SM and to probe new physics

Until now, we know

- The Elementary Constituents of Matter.
- The forces that control their behaviour at the most basic level.

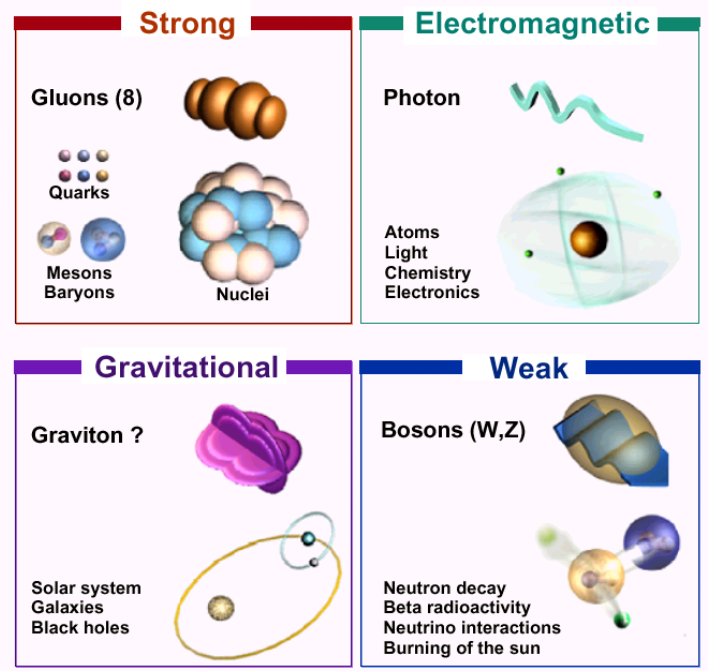
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3



Unify the 4 fundamental forces?

History of Unification

atoms

electric magnetic

planets apple

electromagnetism

Quantum mechanics

gravity mechanics

γ-decay

Special relativity

GR

Quantum ElectroDynamics

β-decay

Weak force

Electroweak theory

α-decay

Strong Force

String theory?

Grand Unification?

James Clerk Maxwell (~1864)

$$\vec{\nabla} \cdot \vec{D} = \rho$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

Modern Language

$$\Box \Phi^{\mu} = \frac{J^{\mu}}{c \varepsilon_o}$$

Electricity

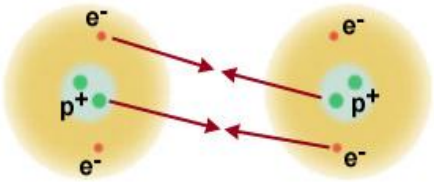
Magnetism

ElectroMagnetism

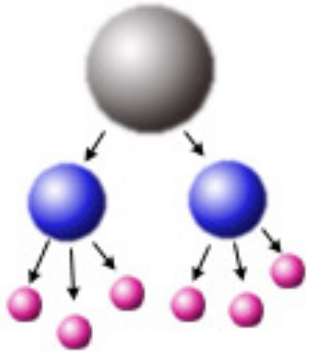
Light

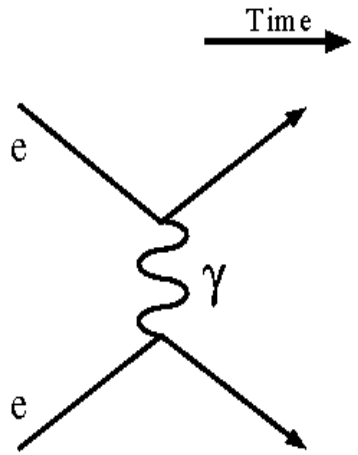
Three Become one

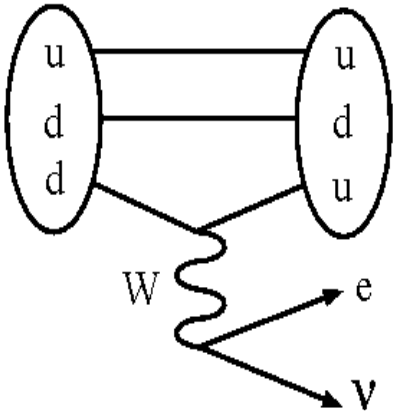
Electroweak Unification



- **Electromagnetic -**
  - Binds atoms together
  - Long range force
  - Force carrier is the photon
  - Acts on charged particles
- **Weak -**
  - responsible for the decay of massive quarks and leptons into lighter quarks and leptons. i.e. nuclear decay - β-decay
  - Short range force
  - Force carriers are
    - W^+, W^- and Z^0 bosons
  - Acts on quarks and leptons
- **Combined into the Electroweak force**







β–Decay:

$n \rightarrow p\, e\, \nu$

Weinberg, Glashow, Salam, 1979 Nobel Prize

The Standard Model of Particle Physics

- Matter fields (make up all visible matter in the universe)
  - Fermions (Spin 1/2)

Lepton

(No Strong Interaction)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e_R^- \qquad \mu_R^- \qquad \tau_R^-$$

Quarks

(q)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad u_R \quad u_R \qquad c_R \quad c_R \quad c_R \qquad t_R \quad t_R \quad t_R$$

$$d_R \quad d_R \quad d_R \qquad s_R \quad s_R \quad s_R \qquad b_R \quad b_R \quad b_R$$

3 families

  - Scalar (Spin 0)

Higgs Boson (July 4, 2012; Higgs or Higgs-Like Boson)

(From Higgs Mechanism —— Spontaneous Symmetry Breaking)

The Standard Model of Particle Physics

- Interactions (mediated by interchanging Gauge Bosons, spin-1 force carrier)

1) Electromagnetic Interaction (QED)

   Photon (massless)

2) Strong Interaction (QCD)

   Gluon (massless) (1979)

3) Weak Interaction

   W^+, W^- and Z Gauge Bosons (1983)

(massive $M_W = 80.385 \pm 0.015$ GeV, $M_Z = 91.1875 \pm 0.0021$ GeV)

$1\ \text{GeV} = 10^9\ \text{eV}$

In SM, the Mass of W-boson, either $W^\pm$ or Z , arises from the Higgs Mechanism

(Without it, Gauge Bosons have to be massless from gauge principle.)

Free Parameters in Standard Model

$SU(3)_{\text{color}} \times SU(2)_{\text{Left}} \times U(1)_{\text{Hypercharge}}$

g_3, g_2, g_1
λ, μ

$\left\{ \begin{array}{l} \alpha_S, \alpha_{\text{em}}, \theta_{\text{Weak mixing}} \\ V(\text{vacuum expectation value}) \\ m_H(\text{Higgs Boson mass}) \end{array} \right\}$

This set can be traded by
$\alpha_S, \alpha_{\text{em}}, G_F, m_Z, m_H$

(3) Lepton masses
(e, μ, τ) m_ν's=0
(6) Quark masses
(u, d, s, c, b, t)

Mixing of quark weak eigenstates and mass eigenstates → 3 angles and 1 phase (CP violation)

(1) Strong CP phase

→ Total of 19 free parameters.
So far, all experimental data agree with the prediction of SM.

To include neutrino masses (suggested by Neutrino Oscillation data) in the SM

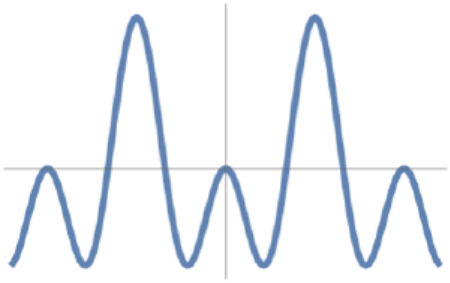
- For Dirac Neutrinos
  → Add 3 masses and 3 mixing angles with 1 CP violation phase
- For Majorana Neutrinos
  → Add 3 masses and 3 mixing angles with 3 CP violation phase

The Standard Model of Particle Physics

- **Mathematical model that explains the hundreds of particles and their complex interactions using:**
  - **6 quarks**
  - **6 leptons**
  - **3 forces (Electromagnetism, Weak and Strong)**
- **The Standard Model is not perfect:**
  - There is no Cold Dark Matter candidate.
  - We don't understand the pattern of particles masses.
  - Why are there only 3 families of quarks and leptons?
  - Do protons decay?
  - Why is there so little antimatter in the universe?
    It requires CP violation. (Kobayashi, Maskawa; Nobel Prize 2008)
  - Why is gravity so weak (in particle interaction)?
- **We need to go beyond the Standard Model**

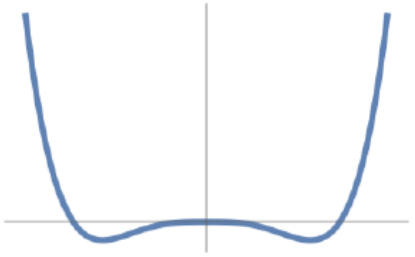
Different Shapes of Higgs Potential in New Physics Models

Pseudo Nambu-Goldstone Higgs



$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

Coleman Weinberg Higgs



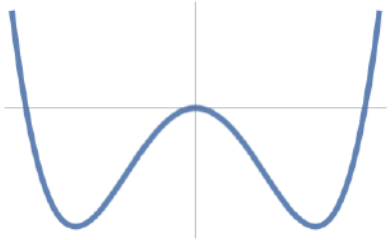
$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

Tadpole-induced Higgs

$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Very different analytic Higgs behavior from SM

Landau-Ginzburg Higgs



$$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

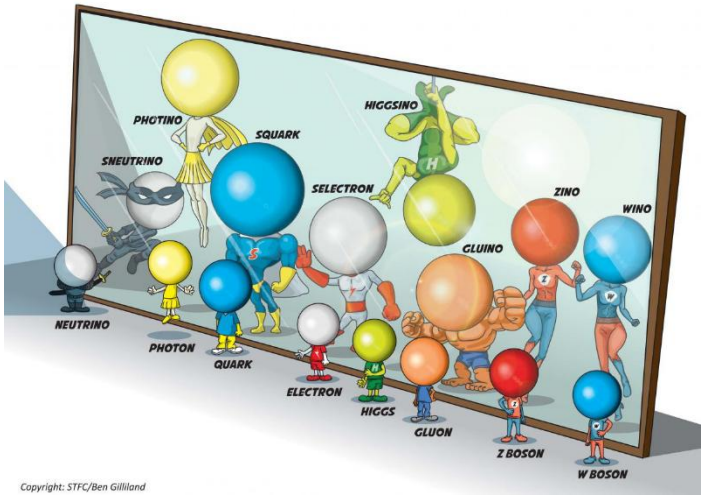
New Physics Models
(Beyond the Standard Model)

- Maxwell took a big step toward this goal when he unified electricity and magnetism, and physicists now understand that at high energies the electromagnetic and weak forces are aspects of the same force.

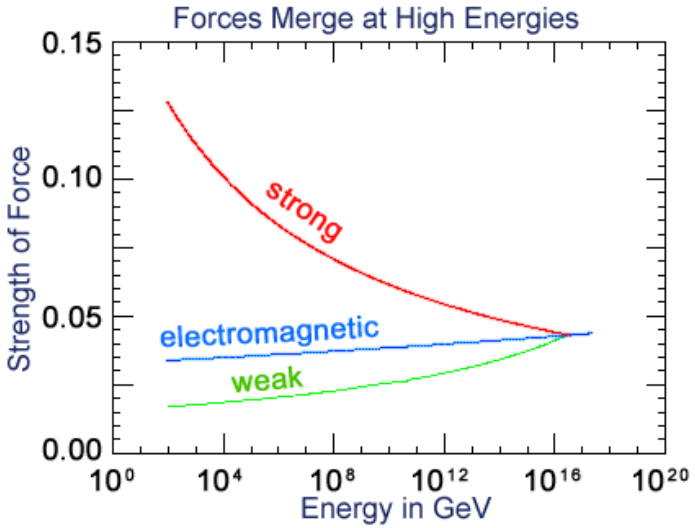
- To also unify strong interaction (and gravity)
  - Grand Unified Theory (GUT)
  - Supersymmetry (SUSY)
  - Extra Dimensions
  - String Theory

New Physics Models of Particle Physics

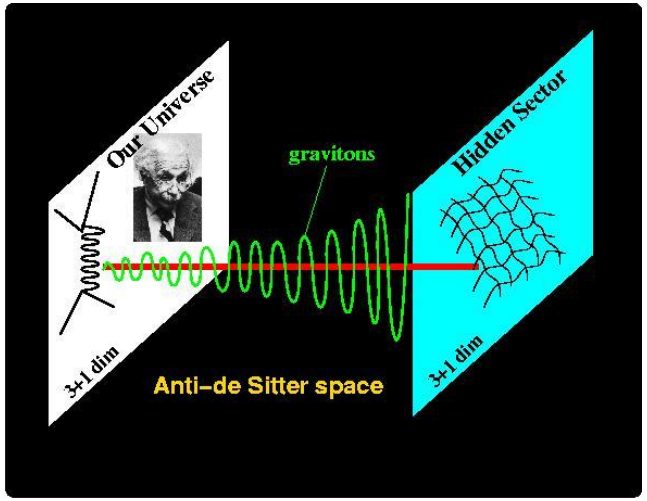
SUSY

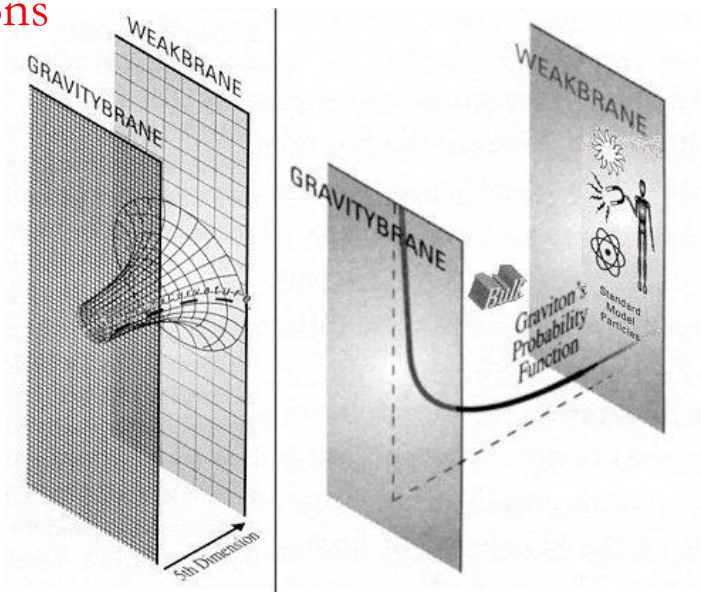


GUT



Extra dimensions





Summary

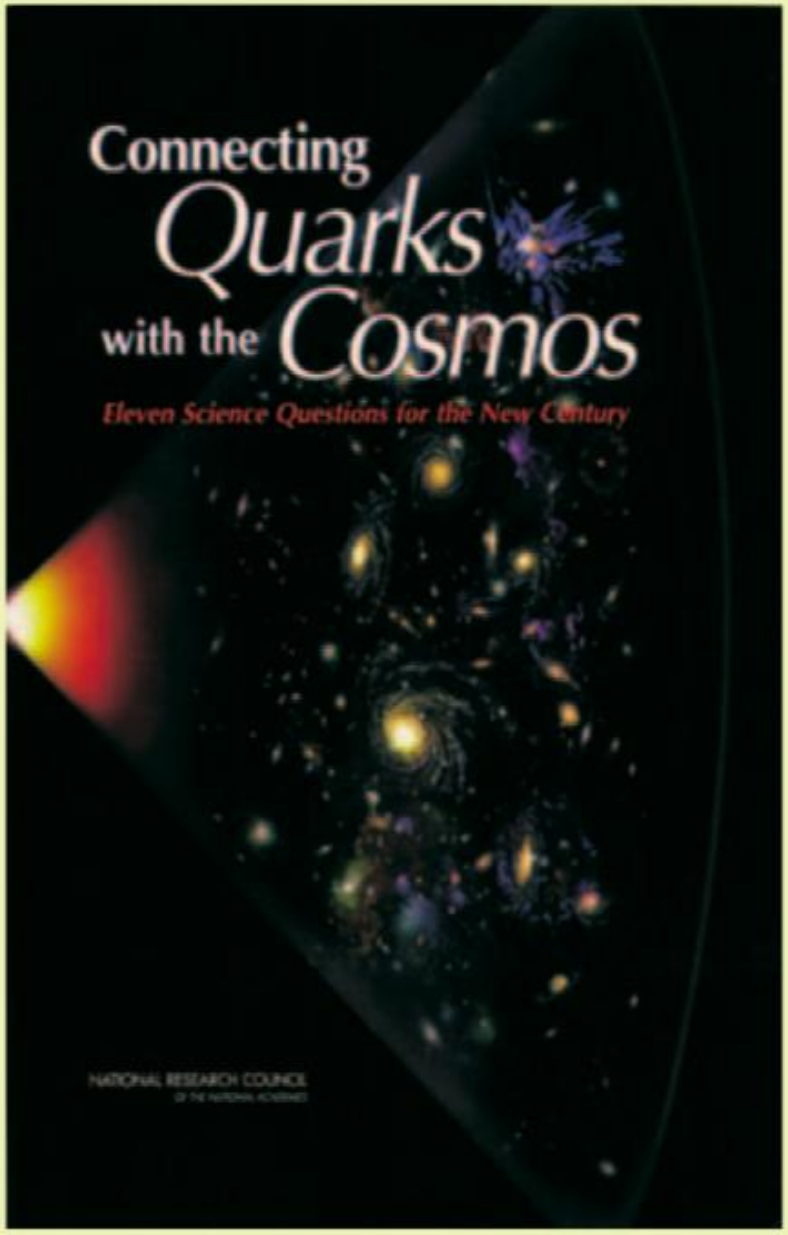
- The world is made up of quarks and leptons
- These particles interact through 4 different forces
- The Standard Model of Particle Physics works -- but is limited in what it can do.
- The Standard Model of Cosmology works – our universe is expanding with acceleration.
- We are still missing several pieces of the puzzle
- Work is underway to fill in the holes
- Mostly importantly, to find the unexpected!

Pretty cool stuff!


Thank you!

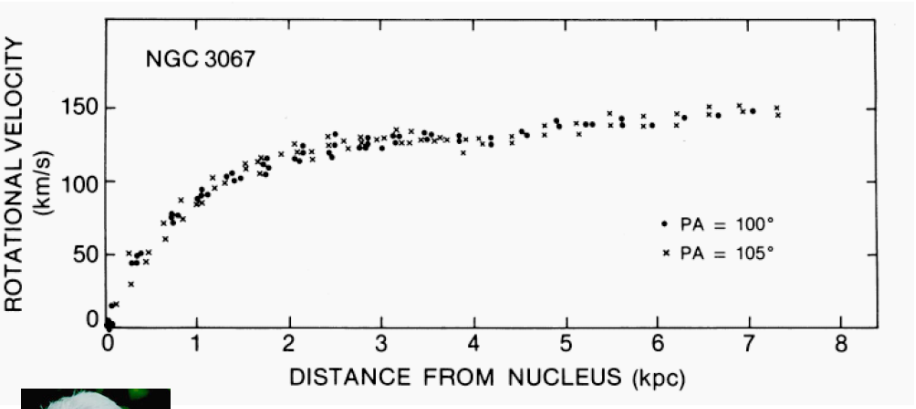
Backup Slides

The Eleven Questions Identified by the *Connecting Quarks with the Cosmos* Report



1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies?

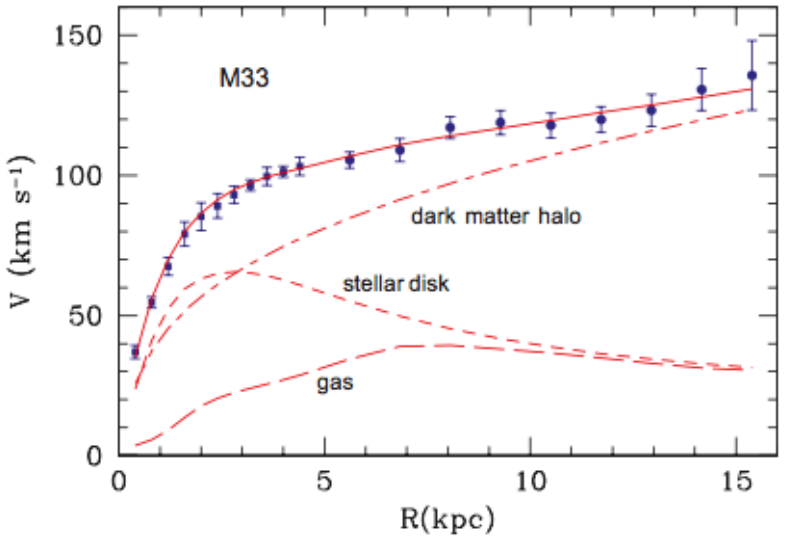
Evidence of Dark Matter

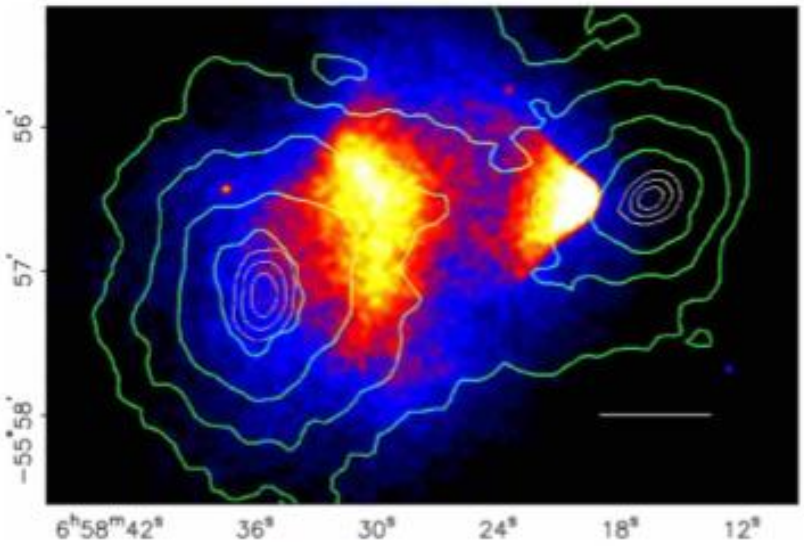


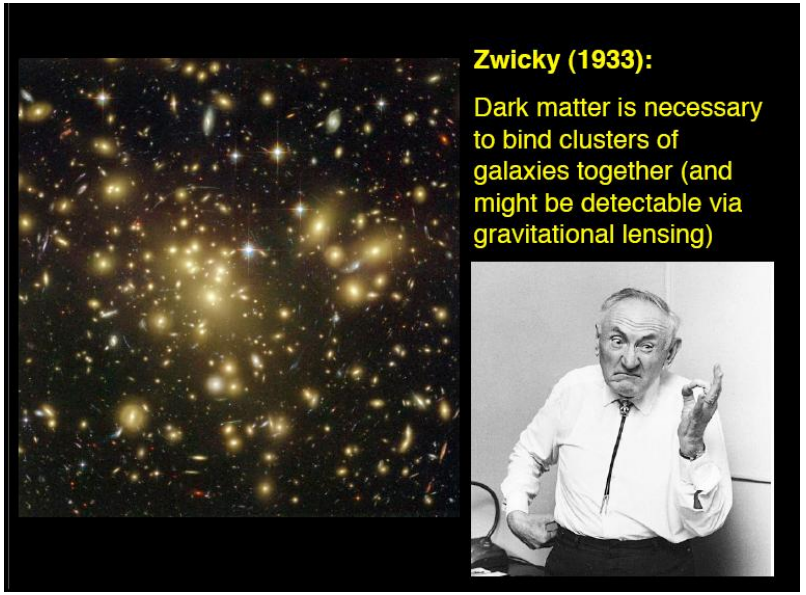
Vera Rubin

Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L greater than 100."







Exercise

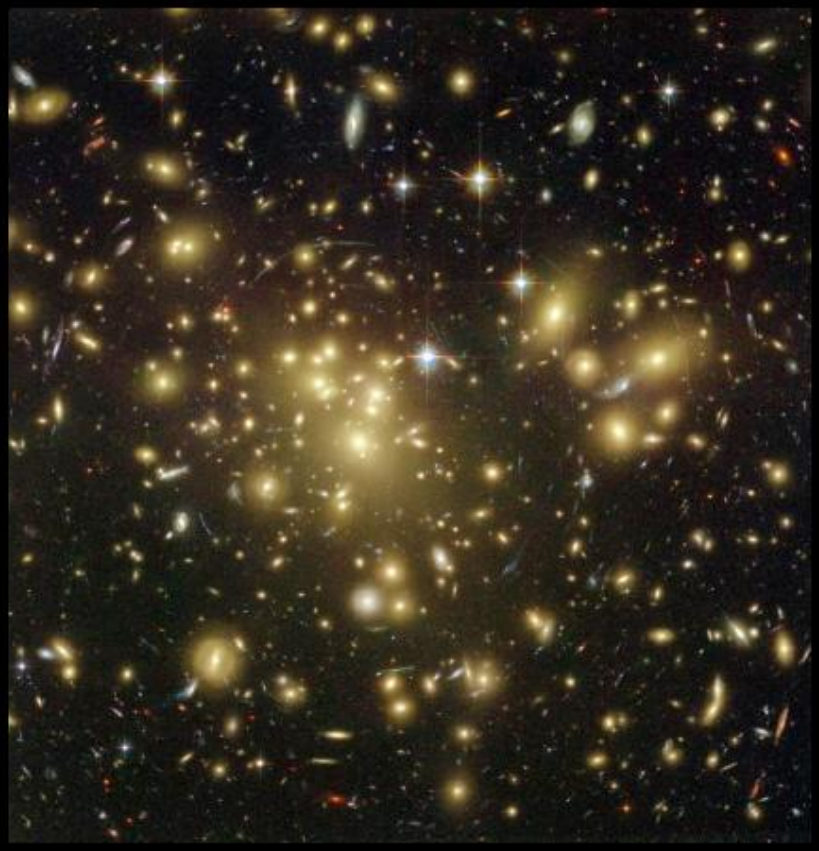
- **Exercise: How can we use knowledge of velocities to find the mass of the galaxy?**

$$v \sim \frac{1}{\sqrt{R}}$$

- This is the same as Kepler's 3rd law, which can be derived from Newton's laws:
- $F = ma = G\,mM/R^2$; So $a = G\,M/R^2$;
- Also $a = v^2/R$, so $v^2 = G\,M/R$
- Assuming the mass does not change with R, i.e., all the mass is well inside the radii R being considered, then the velocity can be used to find the mass, and the velocity is expected to decrease as 1/sqrt(R)

This is not what's found experimentally.

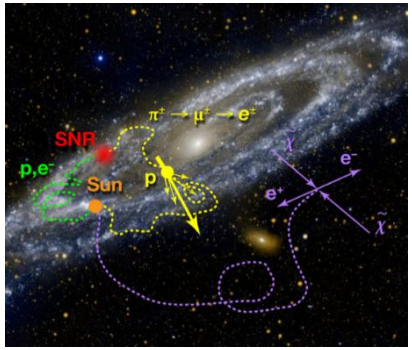
Dark Matter



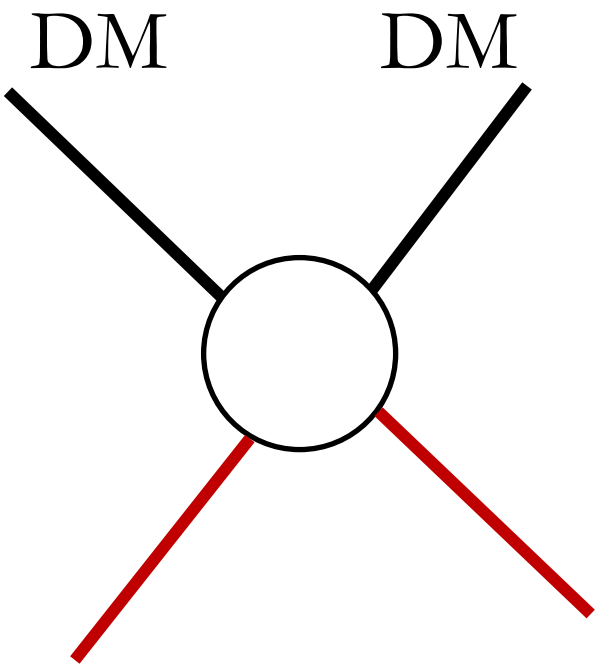
Zwicky (1933):

Dark matter is necessary to bind clusters of galaxies together (and might be detectable via gravitational lensing)

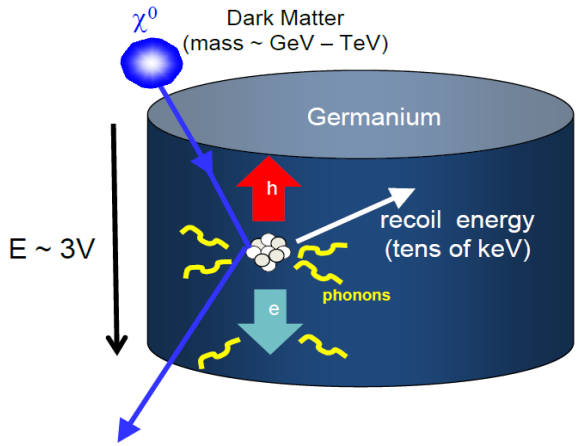
How to probe Dark Matter?



Indirect search



Collider search



Direct search

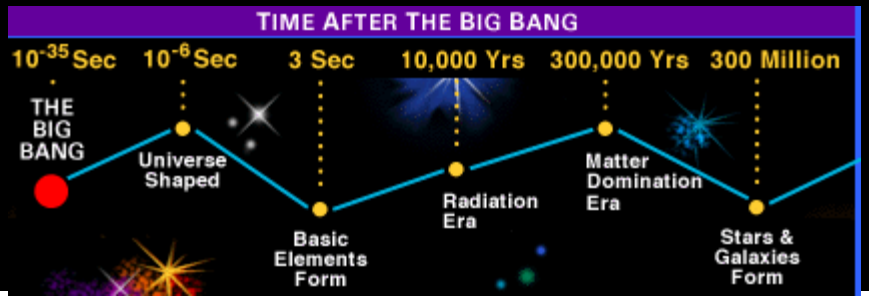
Modern Cosmology

- About 13.8 billion years ago, the universe was in an extremely hot, dense state and began expanding.
- Space itself expanded, and all matter (including Dark Matter) and energy were once much closer together.

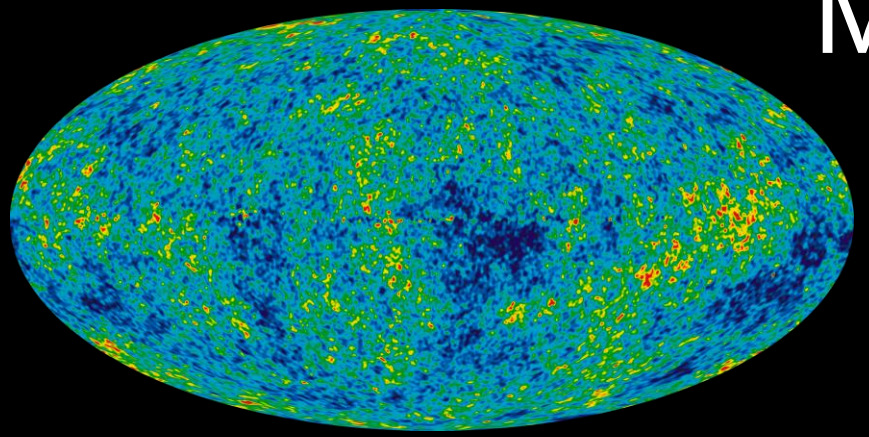
=>

Big Bang Theory

- In the intervening years, the universe has been expanding, cooling as it goes.



Modern Cosmology



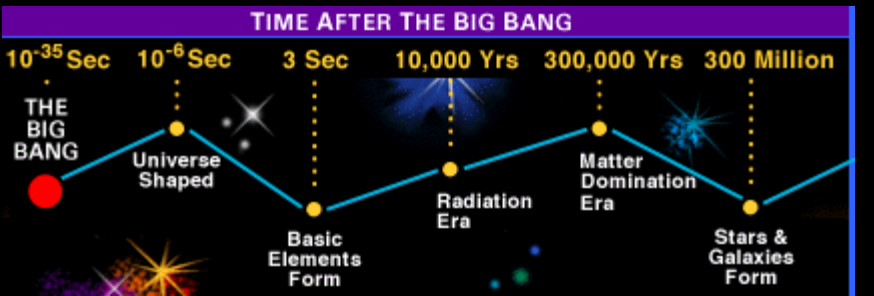
- *Big Bang Theory*
- *2011 Nobel Prize for discovering the accelerating expansion of the Universe through observations of distant supernovae.*

  => Dark Energy



Saul Perlmutter, Brian P. Schmidt, Adam G. Riess, 2011 Nobel Prize

- In the intervening years, the universe has been expanding, cooling as it goes.

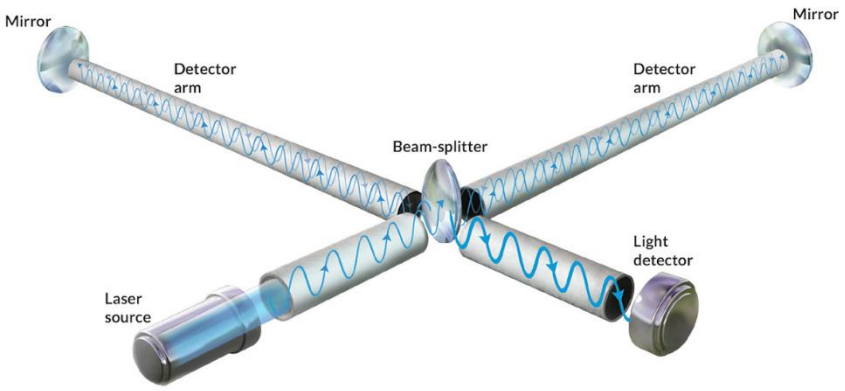


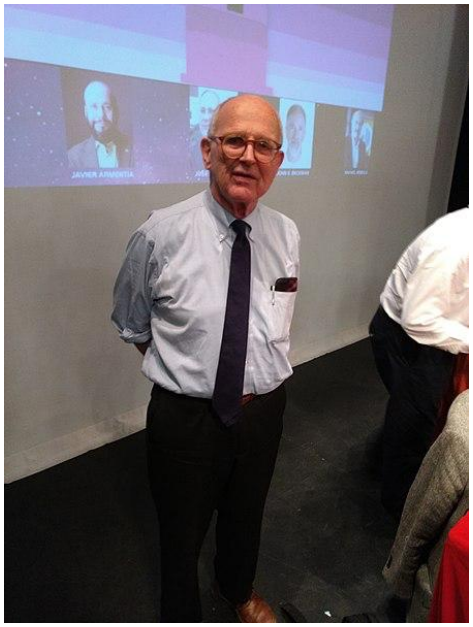
Einstein (1916):

Gravity arises from curvature of spacetime

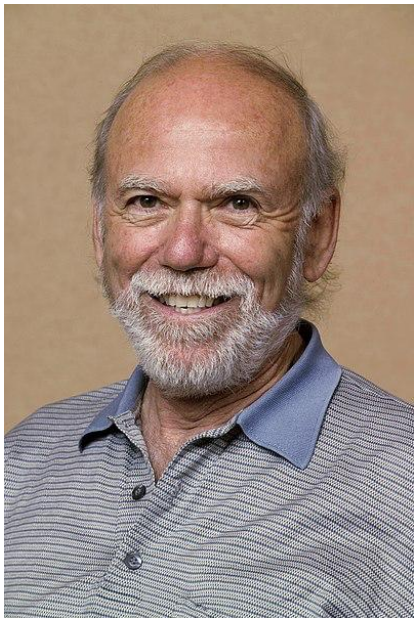
$$G_{ij} = 8\pi T_{ij} - \Lambda g_{ij}$$

LIGO detector and Gravitational waves (2017 Nobel Prize)

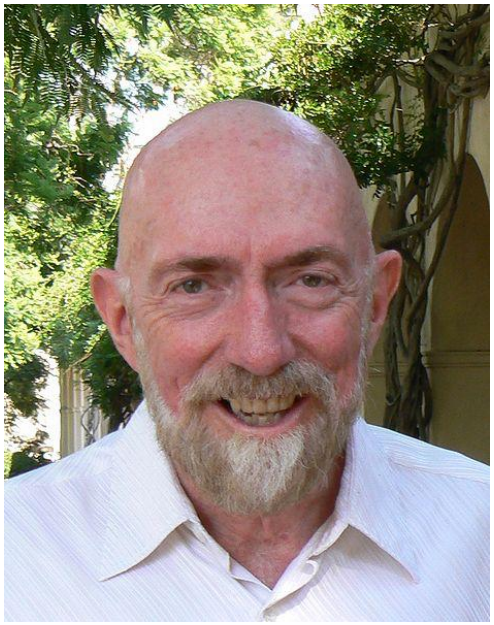




Rainer Weiss

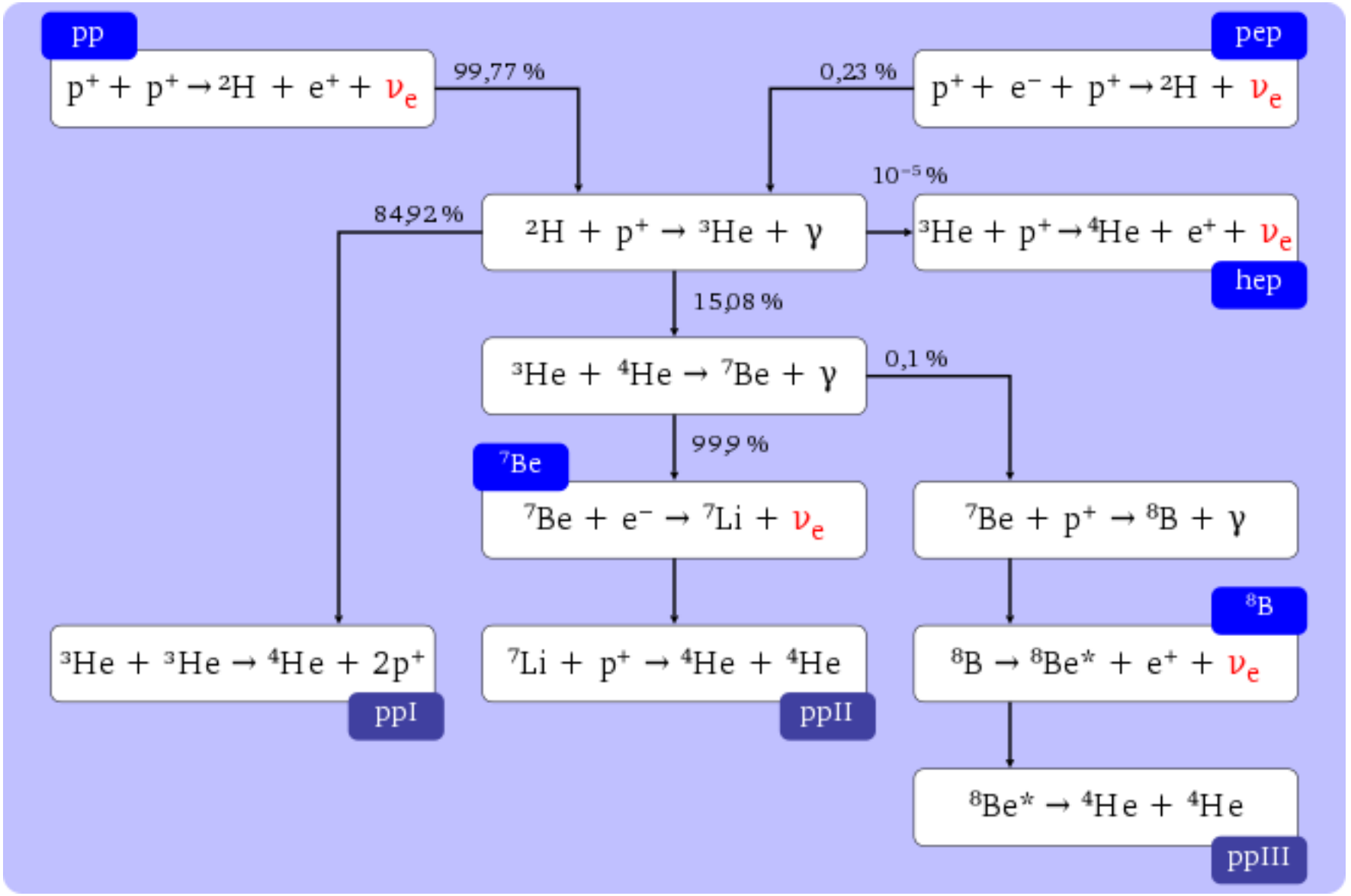


Barry Barish

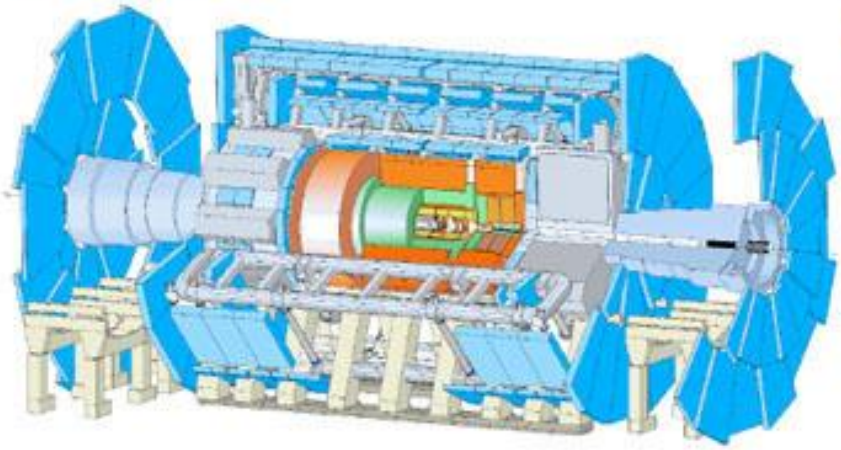


Kip Thorne

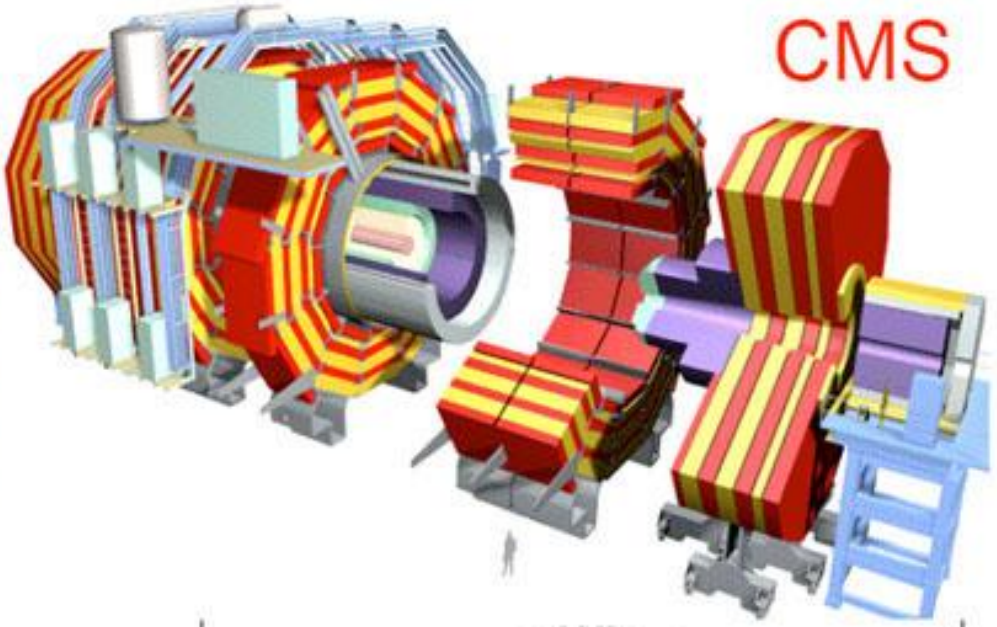
Solar neutrinos (proton–proton chain) in the Standard Solar Model

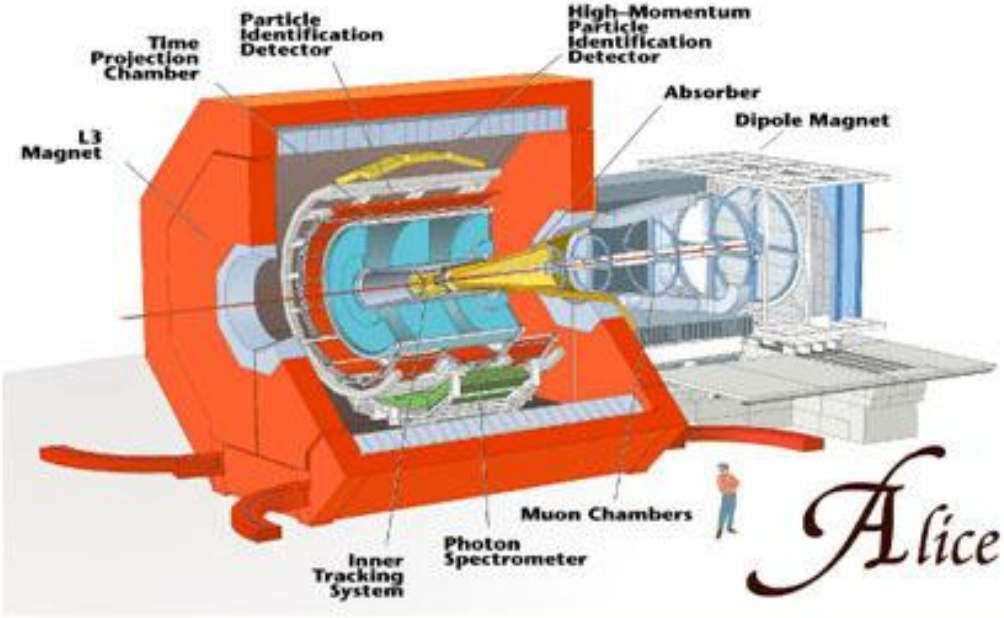


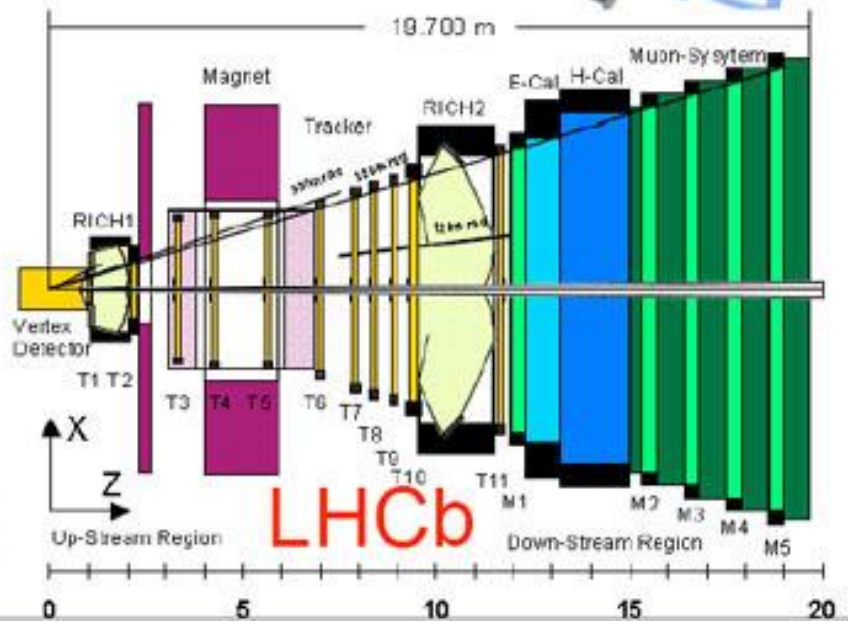
ATLAS



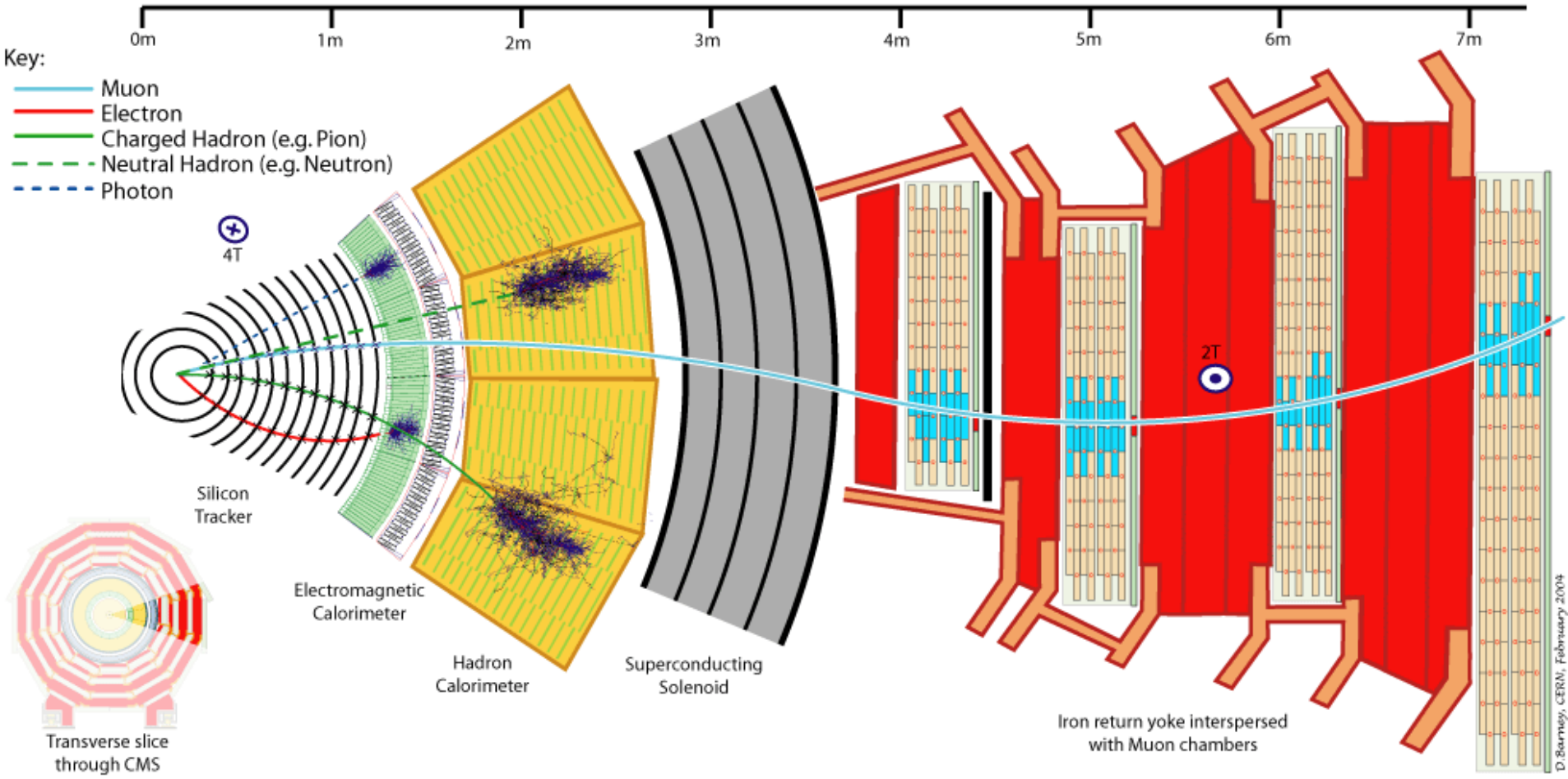
CMS



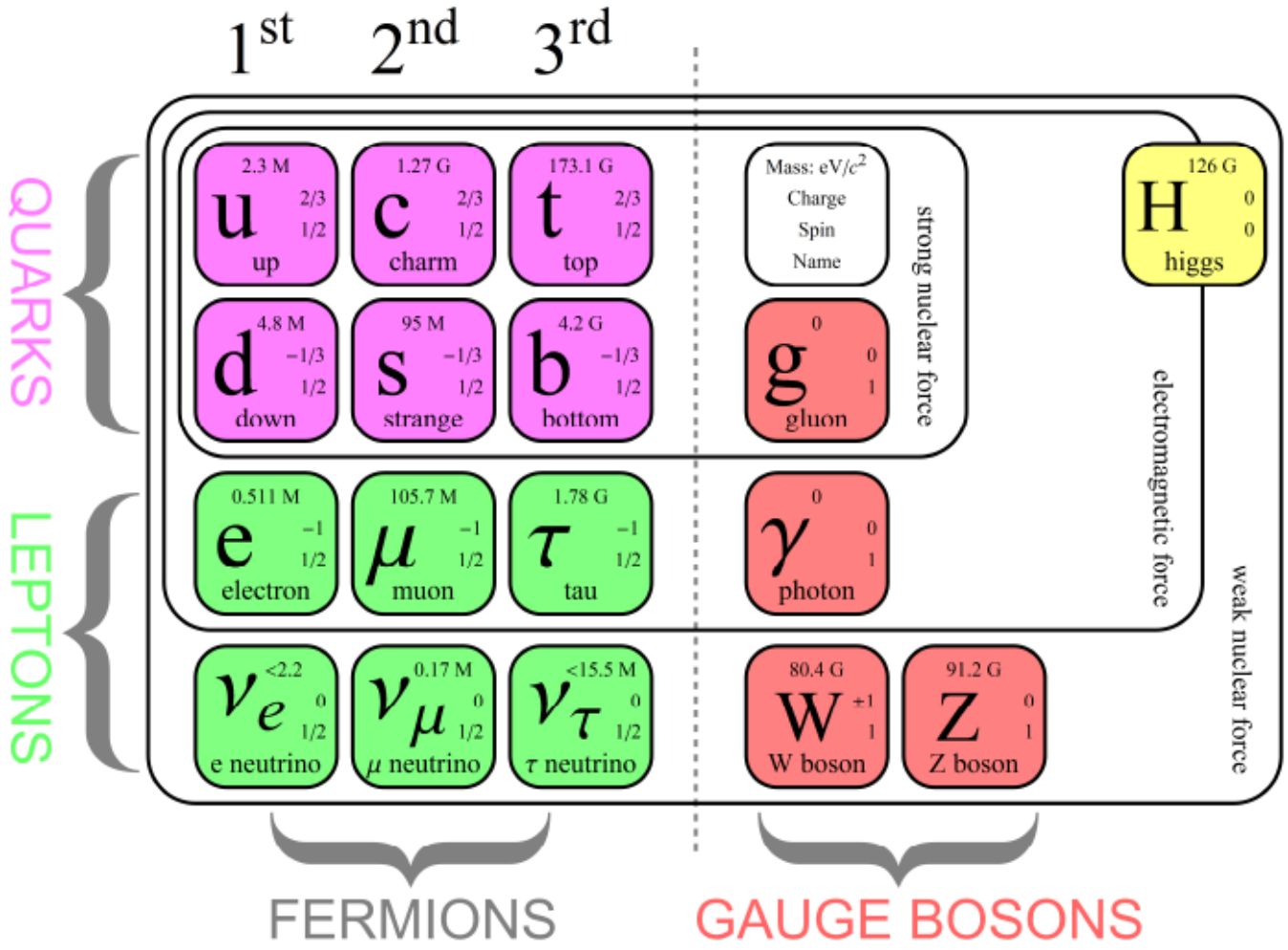

Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice


19.700 m
Magnet
Tracker
RICH2
E-Cal
H-Cal
Muon-System
RICH1
Vertex Detector
T1 T2
T3
T4 T5
T6
T7
T8
T9
T10
T11
M1
M2
M3
M4
M5
X
Z
Up-Stream Region
Down-Stream Region
LHCb
0
5
10
15
20

CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

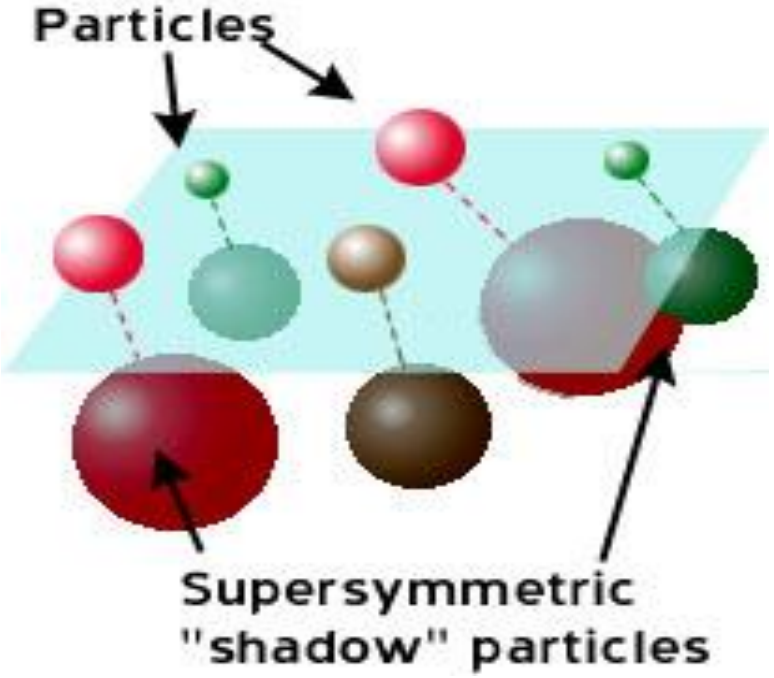
Elementary particles of the Standard Model



Supersymmetry

- Some physicists attempting to unify gravity with the other fundamental forces have come to a startling prediction: every fundamental particle should have a "shadow" particle as its partner.
- This relationship between matter particles and "shadow" particle is called **supersymmetry**.

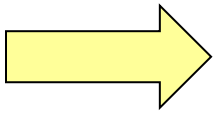
So far, no evidence for Supersymmety has been found. Experiments are underway at Fermilab (USA) and CERN (Europe) to look for them!



- Modern physics has good theories for quantum mechanics, relativity, and gravity. But gravity does not quite work with quantum physics. There are problems caused by our living in three spatial dimensions. If we lived in more than three spatial dimensions, these problems would naturally resolve themselves.
- **String Theory**, one of the recent proposals of modern physics, suggests that in a world with 4 ordinary dimensions (3 space and 1 time) and 7 additional very "small" dimensions, particles are strings and membranes.
  - These extra dimensions could be very small, which is why we don't see them.

Extra Dimensions?

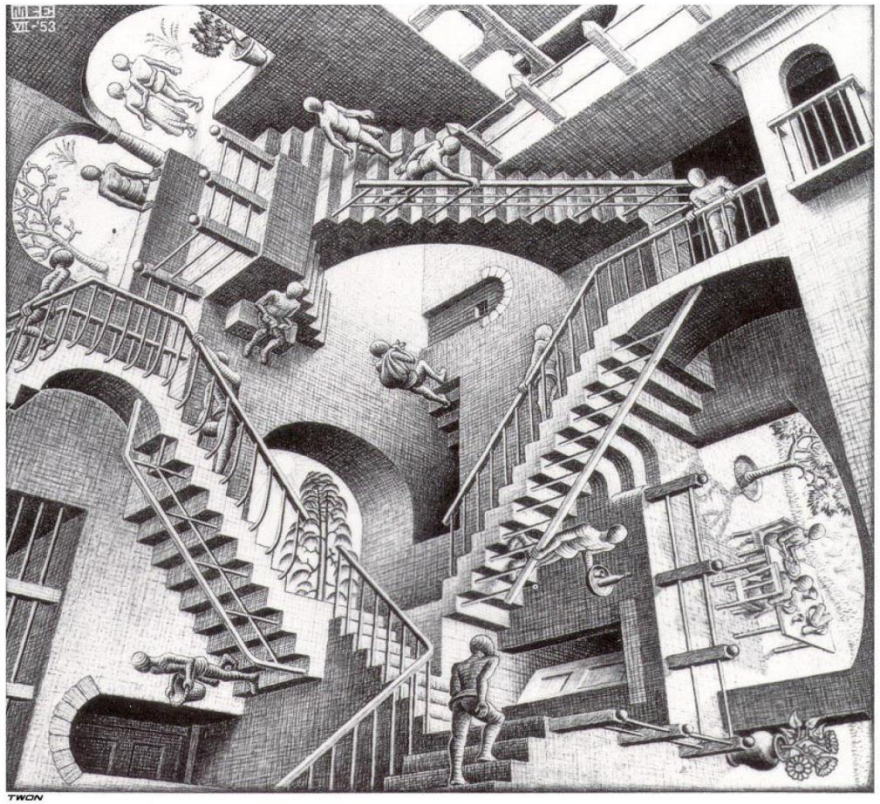
- Think about an acrobat and a flea on a tight rope.
  - The acrobat can move forward and backward along the rope.
  - The flea can move forward and backward as well as side to side.
    - If the flea keeps walking to one side, it goes around the rope and winds up where it started. So the acrobat has one dimension, and the flea has two dimensions, but one of these dimensions is a small closed loop.
  - So the acrobat cannot detect any more than the one dimension of the rope, just as we can only see the world in three spatial dimensions, even though it might well have many more.



Looking for Extra Dimensions

Examples of Compactified Spatial Dimensions

M.C.Escher, Mobius Strip II (1963)



M.C.Escher, Relativity (1953)