Introduction

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8th International Accelerator School for Linear Colliders
Antalya, Turkey, 4-16, December, 2013

1. **Driving force of Science**
2. **Our universe**
3. **Accelerator, another driving force**
4. **Journey to the new world**

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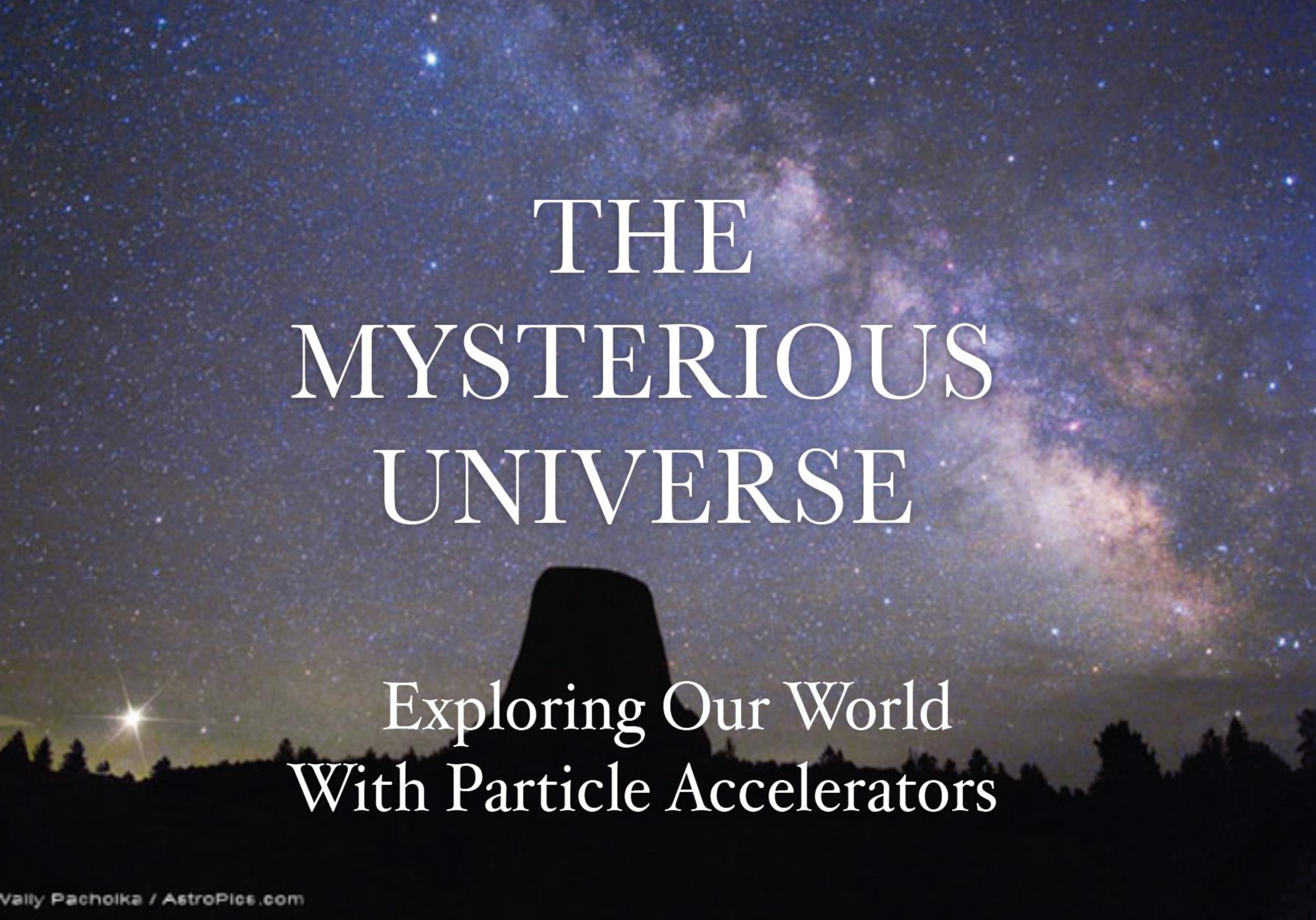

THE
MYSTERIOUS
UNIVERSE
Exploring Our World
With Particle Accelerators
Wally Pacholka / AstroPics.com

Do We really understand our world?

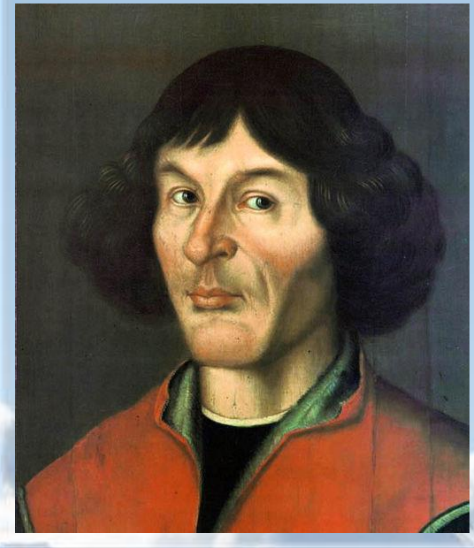
What is the exact meaning of this question?

Remember the scientific revolution in 17th century.

How recognized people the universe before the revolution?

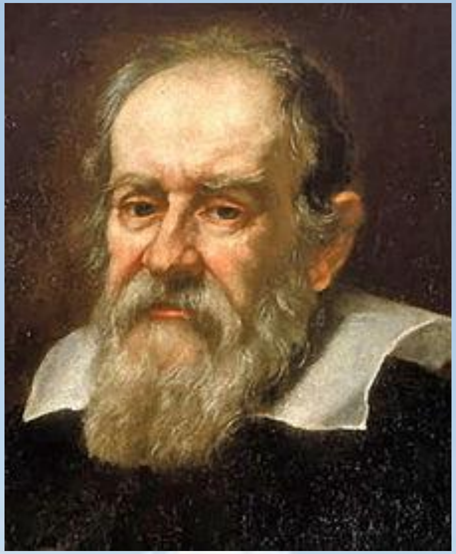
17^{th} century Scientific Revolution

N. Kopernikus

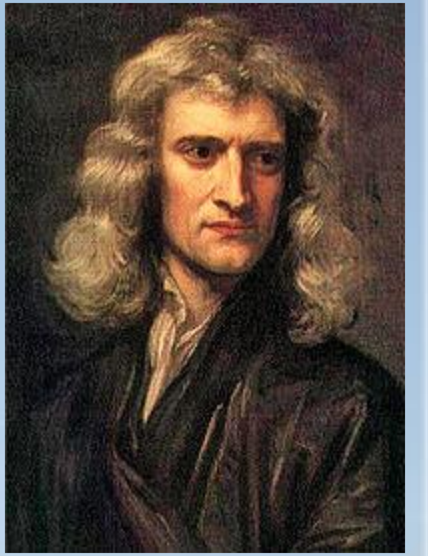


J. Kepler

G. Galilei



I. Newton



Before the revolution

Earth (ground) and Cosmos are ruled by different principles.

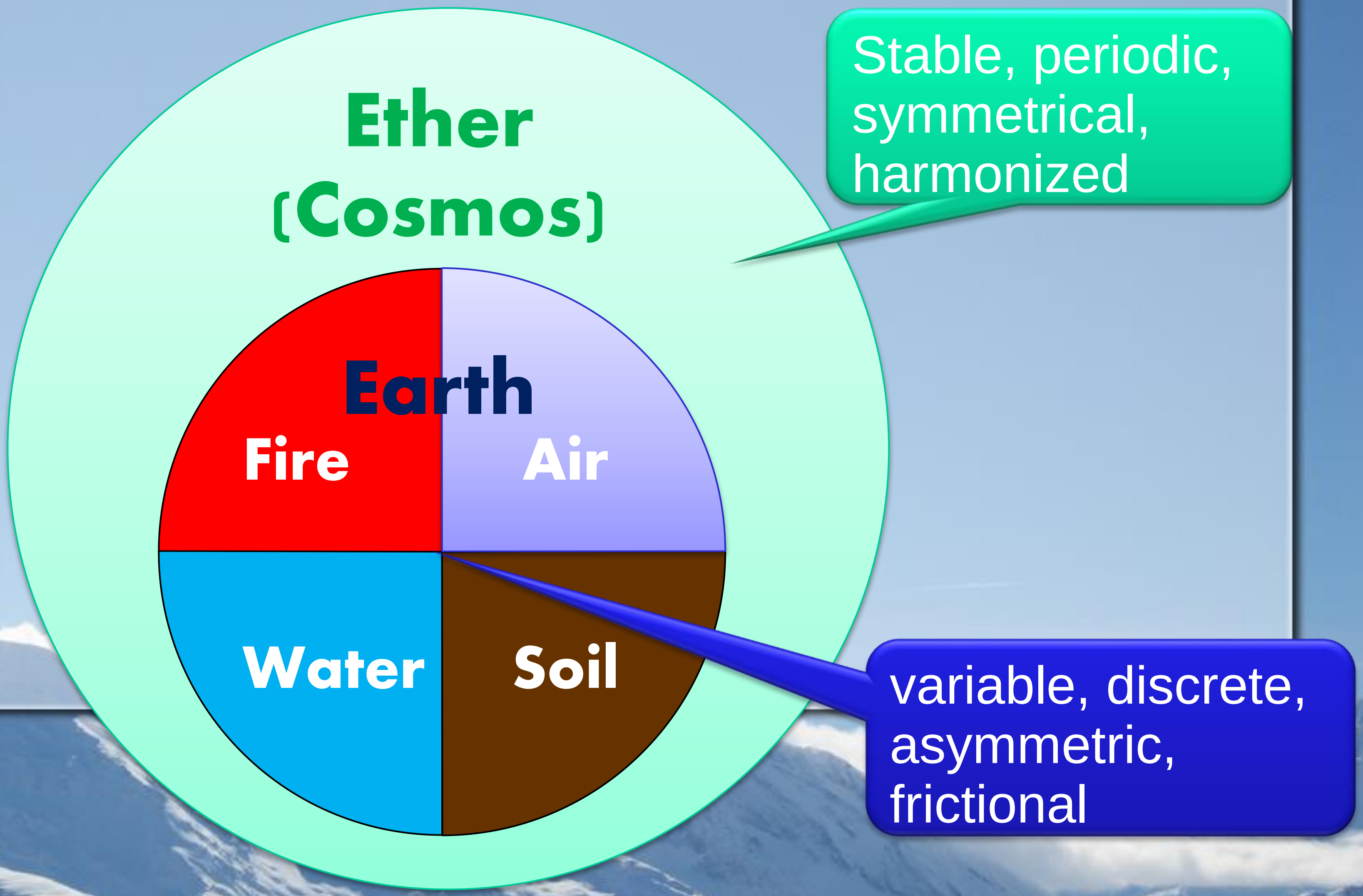
Ground: All object wants to return to his home (earth). All moving object wants to stop.

Cosmos : Motion of stars and planets are stable and periodic. It is symmetrical and harmonized.

-> Derivation : Cosmetic for your beauty !

Cosmos and Earth

Aristotle universe



Physics is Over?

We now know that Aristotle universe is not true.

Is the revolution over? Do we really understand our universe?

Do we really understand our nature by one simple rule?

Nooooooooh!

Although, we believe that we should understand our universe with a simple rule.

We want establish the simple rule. It is our driving force.

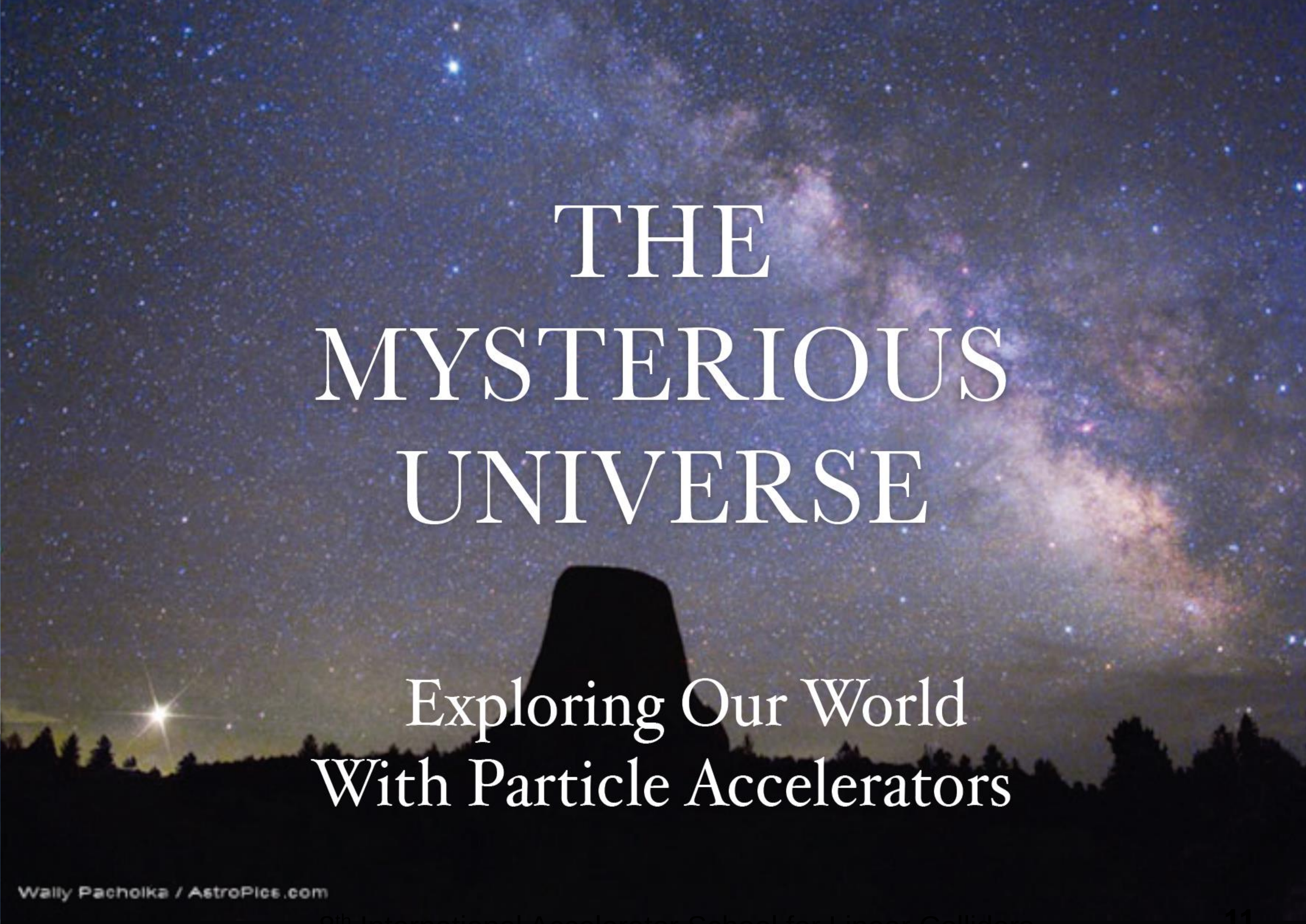
Our driving force

We want **really** understand our universe!

That is our driving force for physics study.

That is a human nature. No question.

But, we have many questions about our mysterious universe.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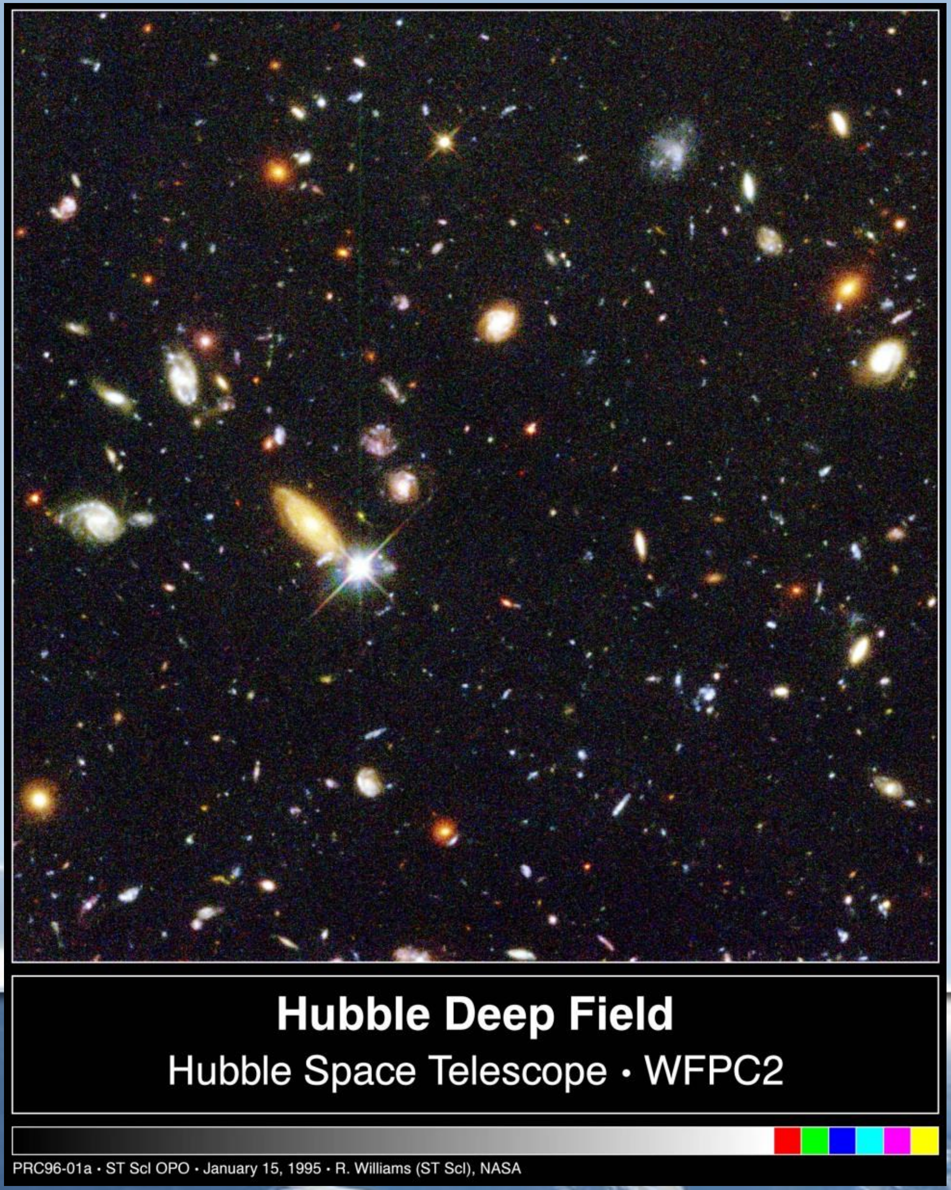
Universe is ruled by Darkforce!

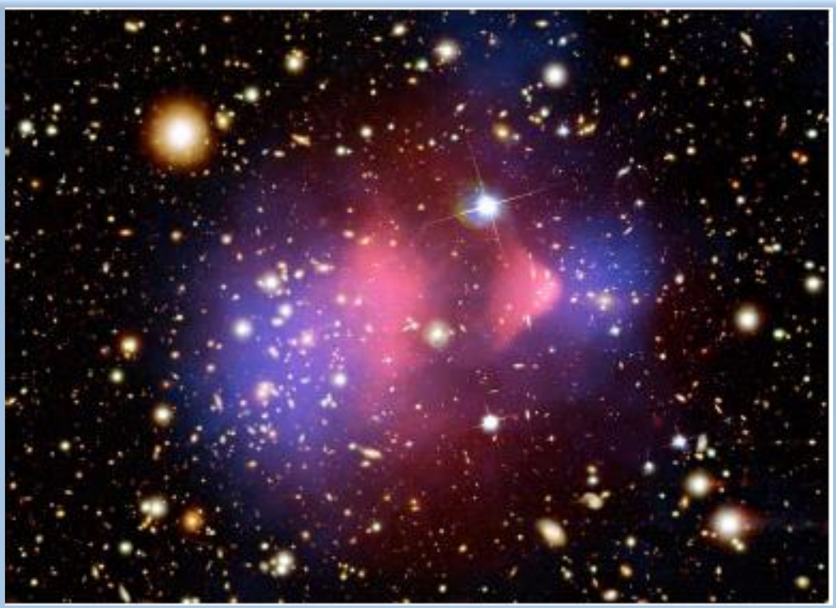
Dark Matter

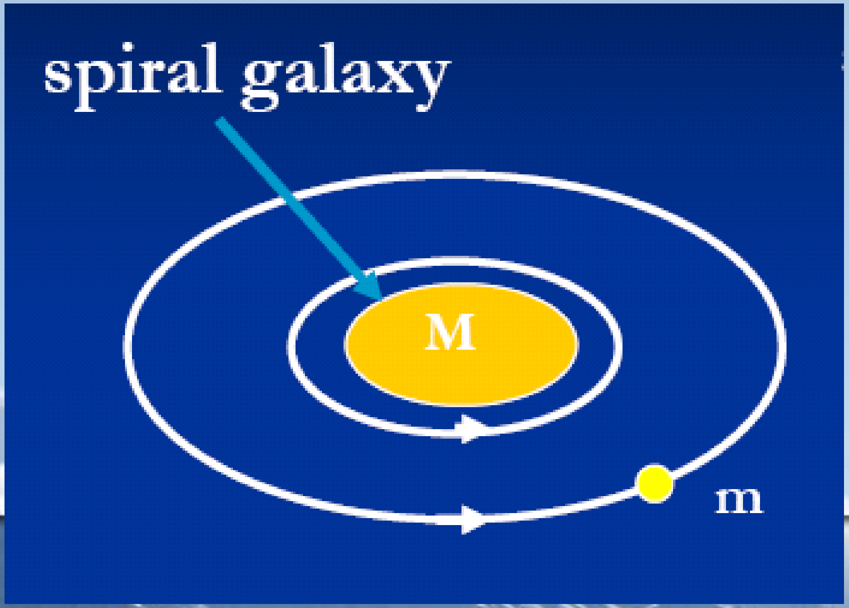


What don't we see?

Dark Matter
Neutrinos
Dark Energy
…
Antimatter !!

Dark Matter





gravity = centrifugal

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

outside of galaxy

$$v = \sqrt{\frac{GM}{r}}$$

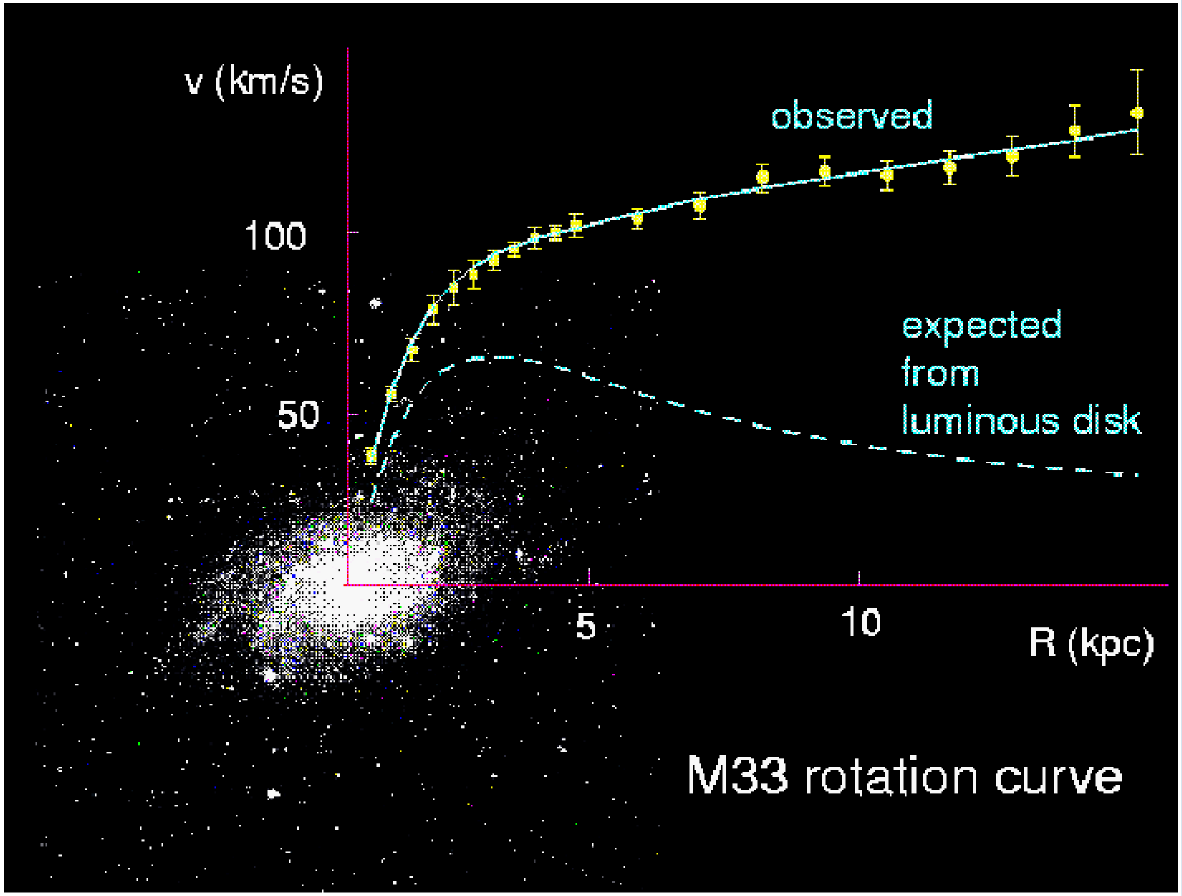
inside of galaxy

$$v = \sqrt{\frac{4\pi}{3}\rho r}$$

Dark Matter in our Galaxy

Rotation speed of the spiral is almost constant over wide distance from the center

~ 0.3 GeV/c^2/cm^3 of Dark Matter exists in our Galaxy

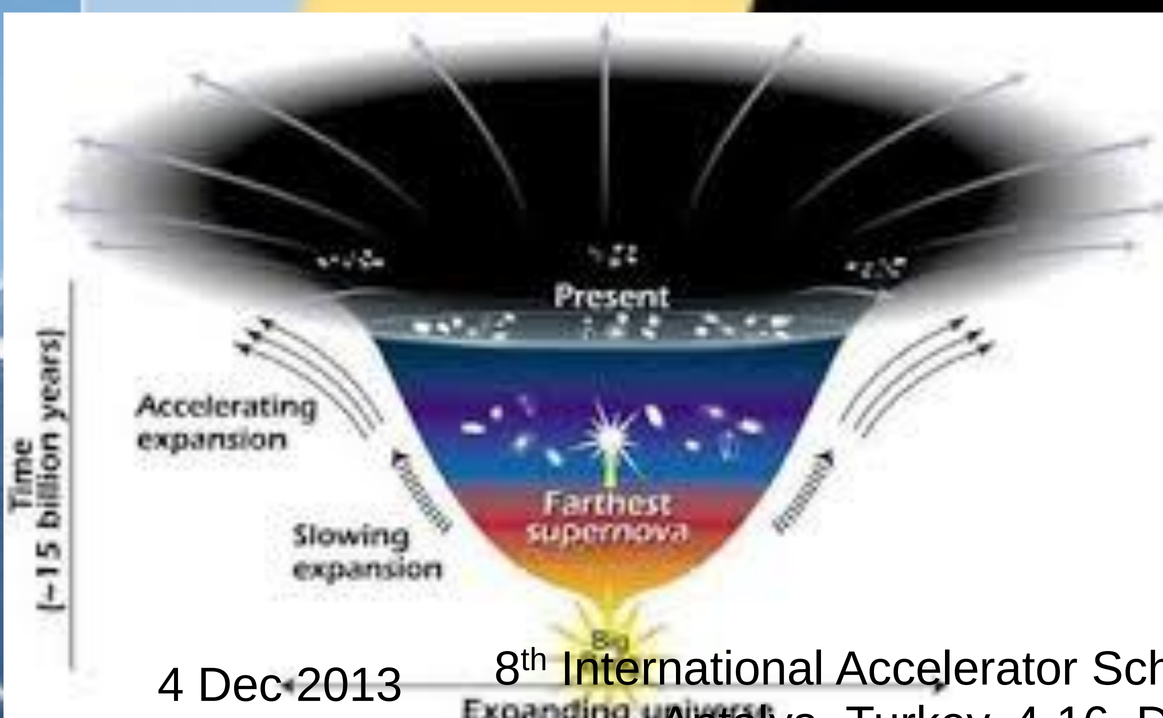


Corbelli & Salucci (2000); Bergstrom (2000)

Dark Energy?

We do not know what is the darkenergy.

This is an unknown pressure which causes accelerated expansion of our universe.

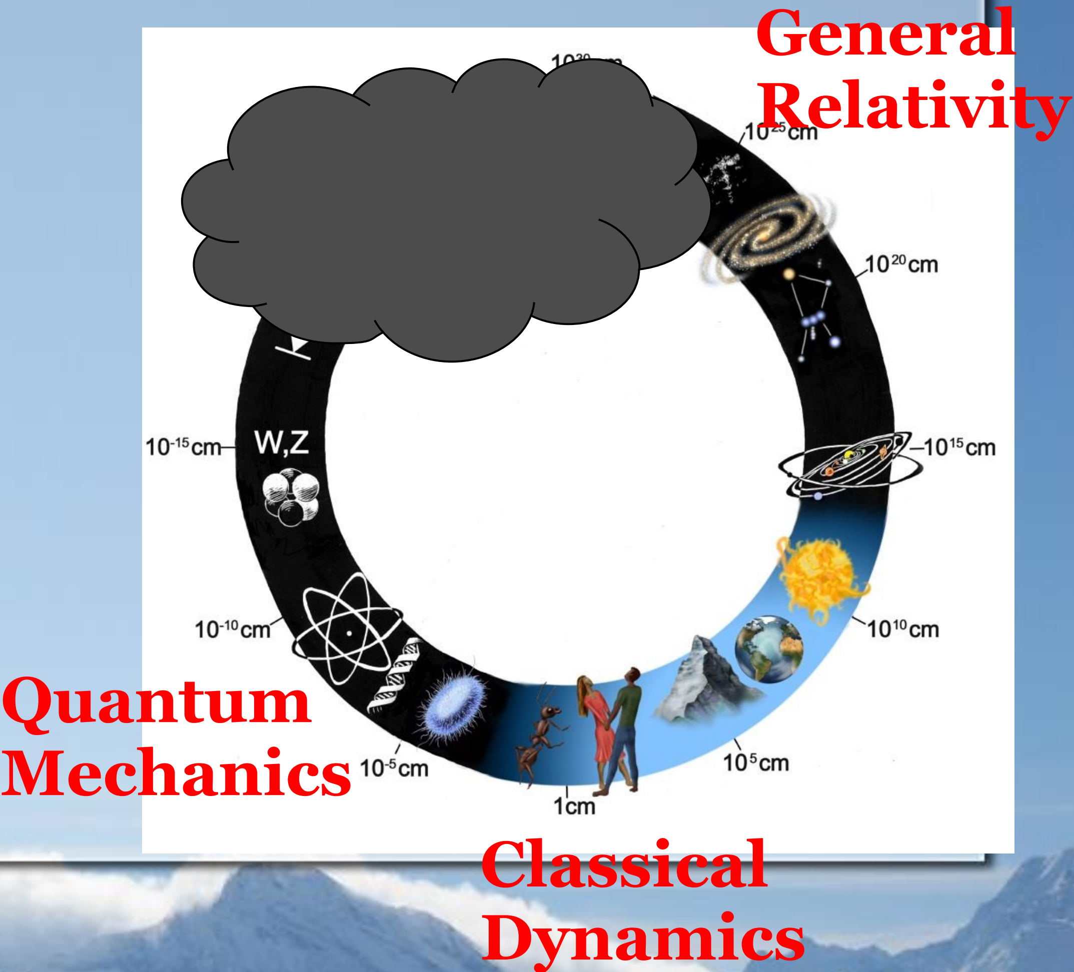


We are alone in this vast universe.
この広い宇宙の中に我々だけ。


ILC/CLIC
LHC
Higgs boson
need to find everything
under the lamp post
learn wher
to go next
H. Murayama

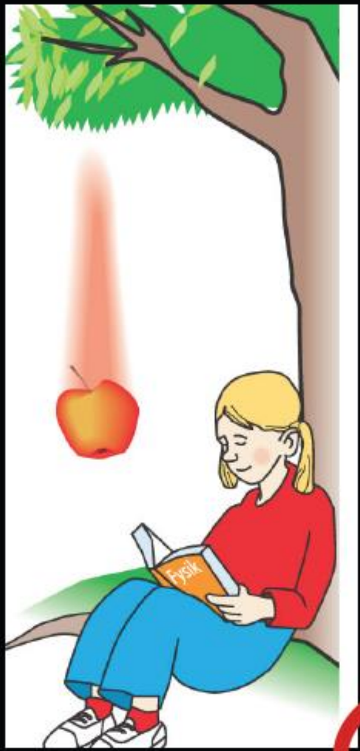
Cloud on the modern physics

- Physics : find universal law of material and interaction.
  - Phenomena in each scale are explained well by a phenomenological theory.
  - Finally, these phenomena would be understand with one unified principle.
  - To reveal the secret, we have to observe new phenomena in larger and smaller scales.



What Holds it all Together?

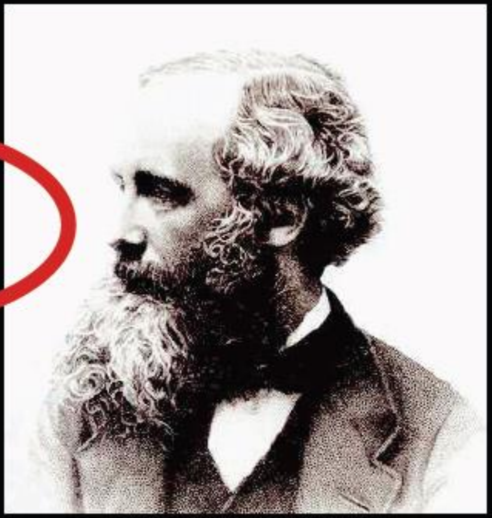
Gravitational Force



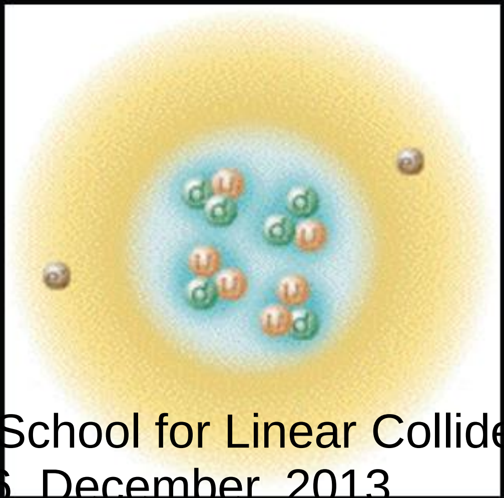
Issac Newton
(1642 - 1727)

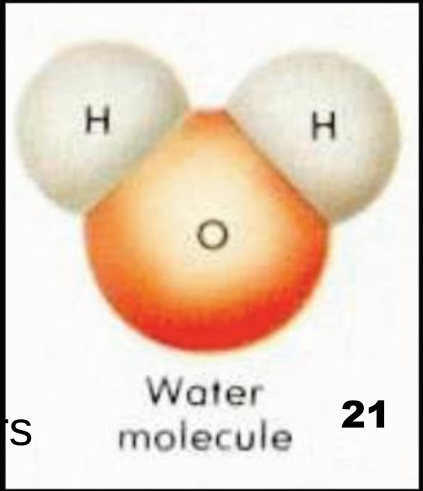
Electromagnetic Force

Photons
γ



James Clerk Maxwell
(1831 - 1879)

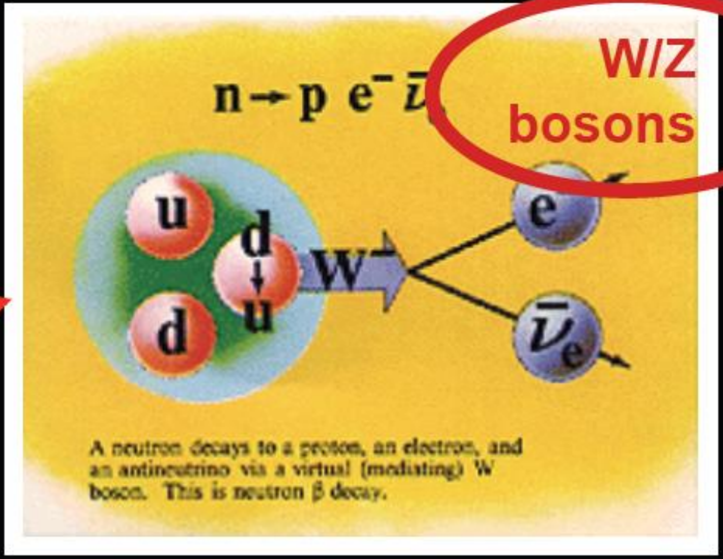


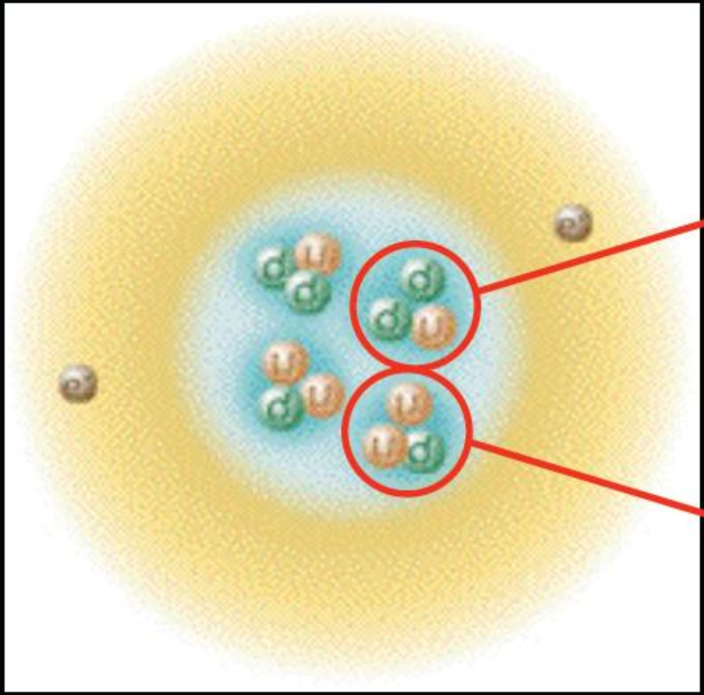


Weak Force

Enrico Fermi
(1901 - 1954)

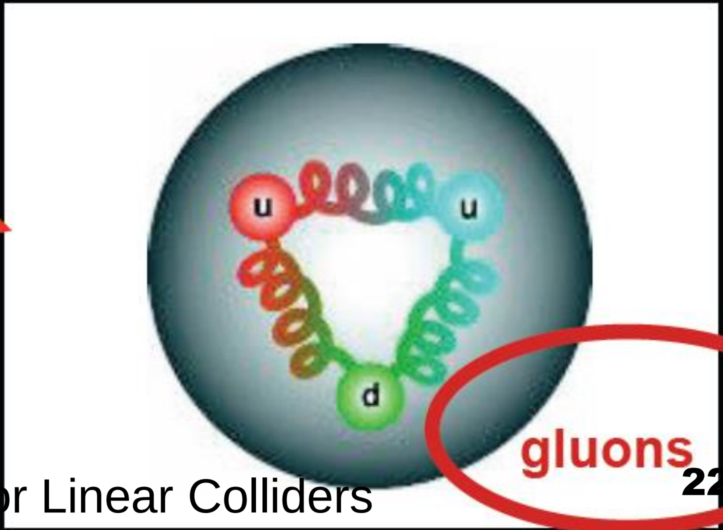
radioactive decays





neutron decay

holding proton, nucleus

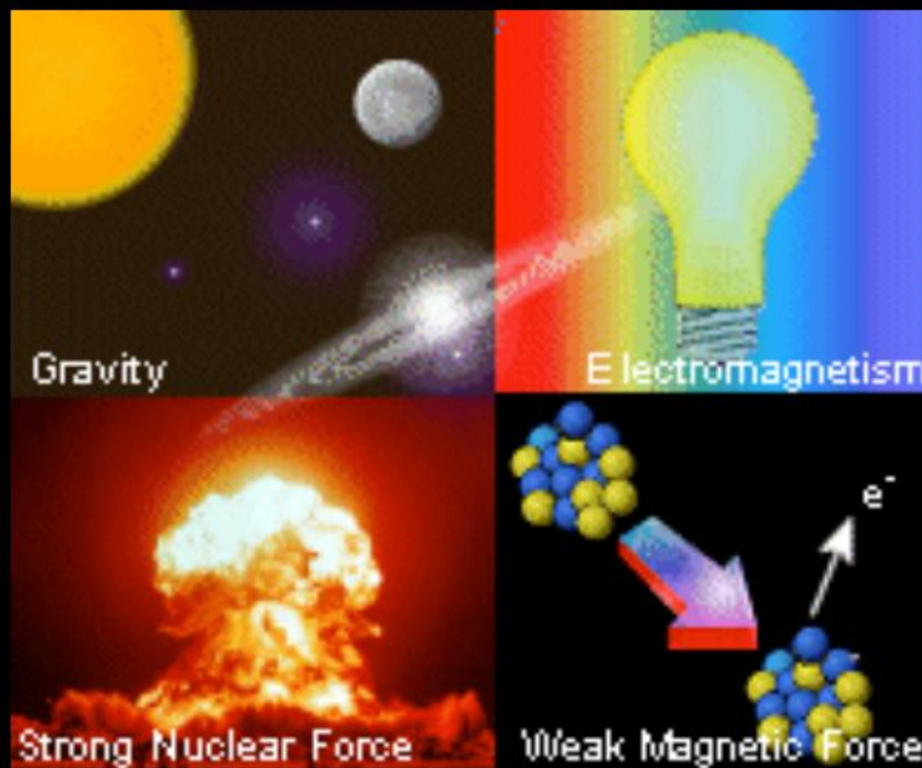


Strong Force

Four Fundamental Forces

graviton

gluon



Gamma ray,
Photon γ

W, Z

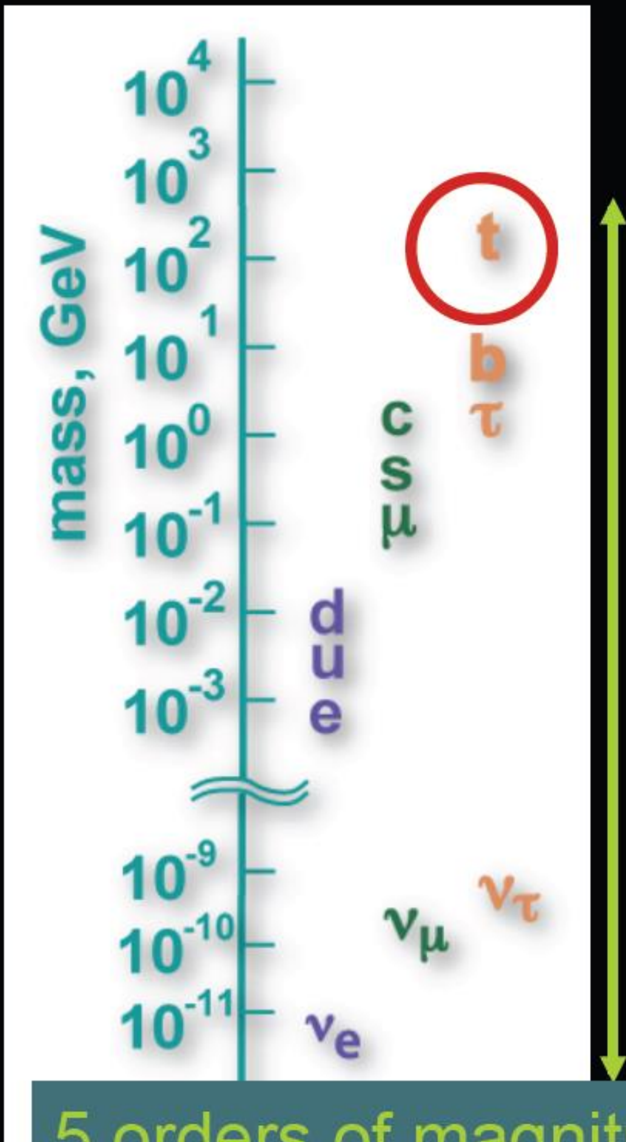
"Mediated" by particles called bosons!

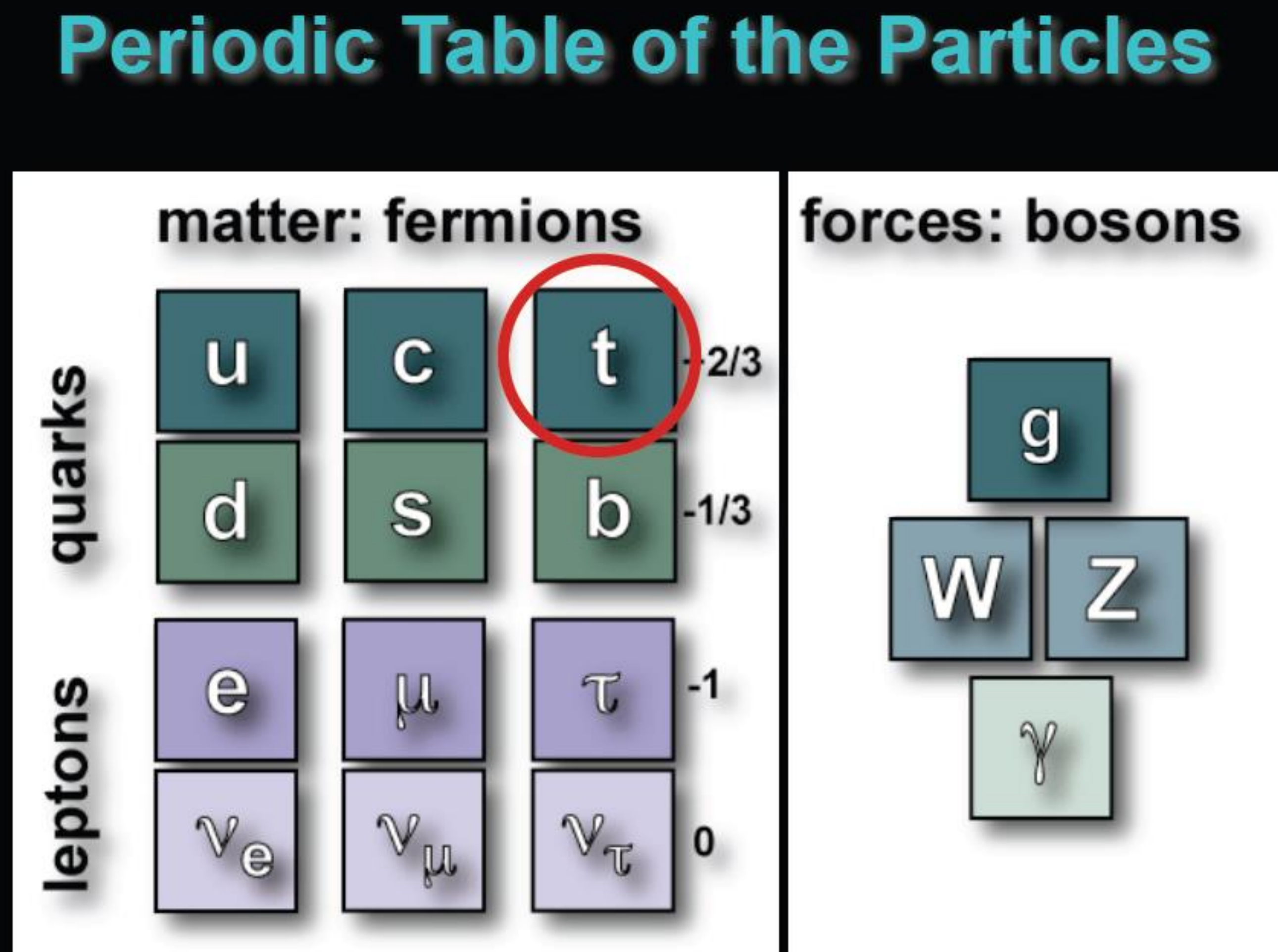
* Graviton not discovered yet.

Periodic table, again.

- In 19th century, many elements were found. These too many elements bothered chemists.
- D. Mendeelev made the periodic table. He assumed many “virtual” elements. Later, these elements were discovered.
- This is very similar that Kobayashi-Maskawa assumed three more quarks to explain CP violation. Later, these three quarks were discovered, too.
- Are there substructure and more fundamental symmetry on quarks, gluons, bosons?

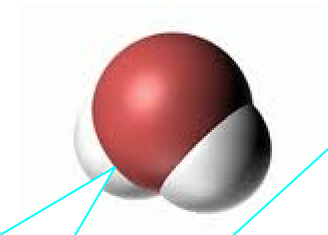
The Standard Model

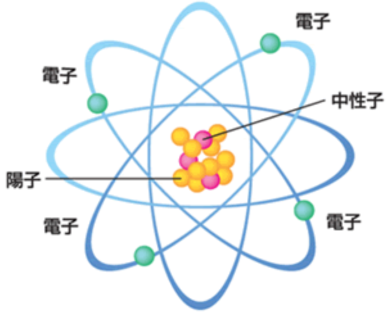


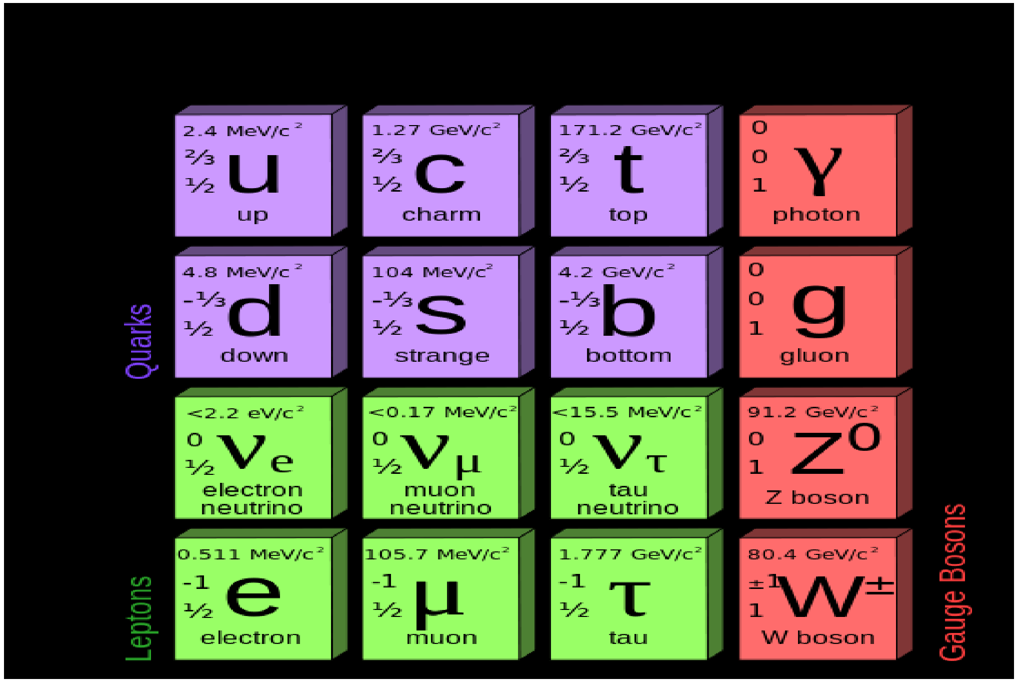


5 orders of magnitude!

Known hierarchy





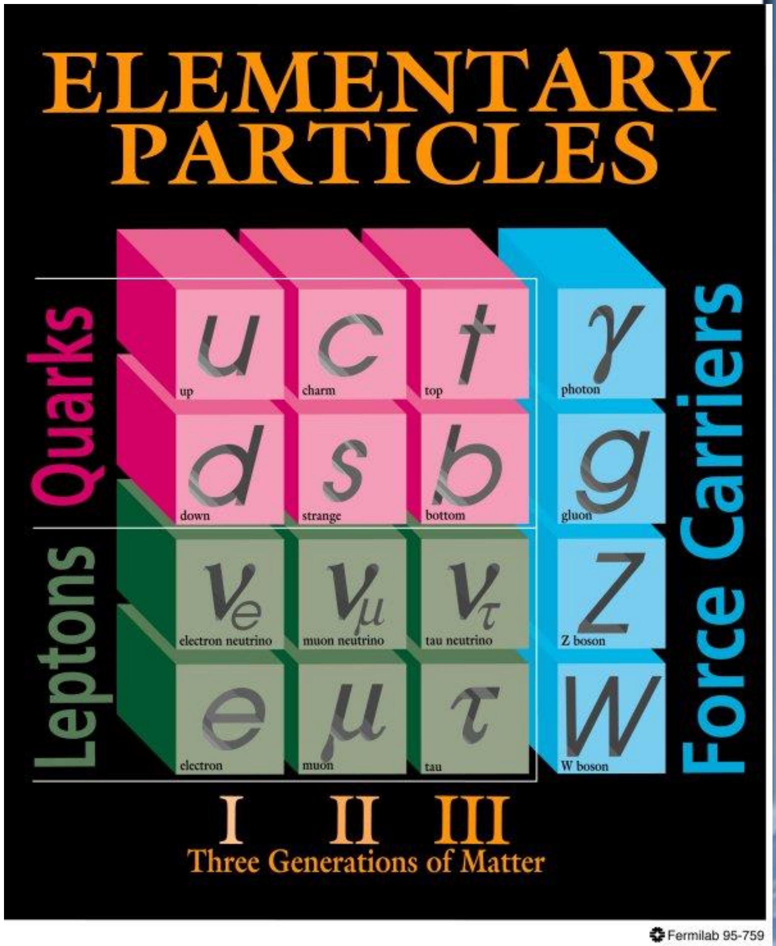


H

The fundamental questions

We do not understand our universe yet.

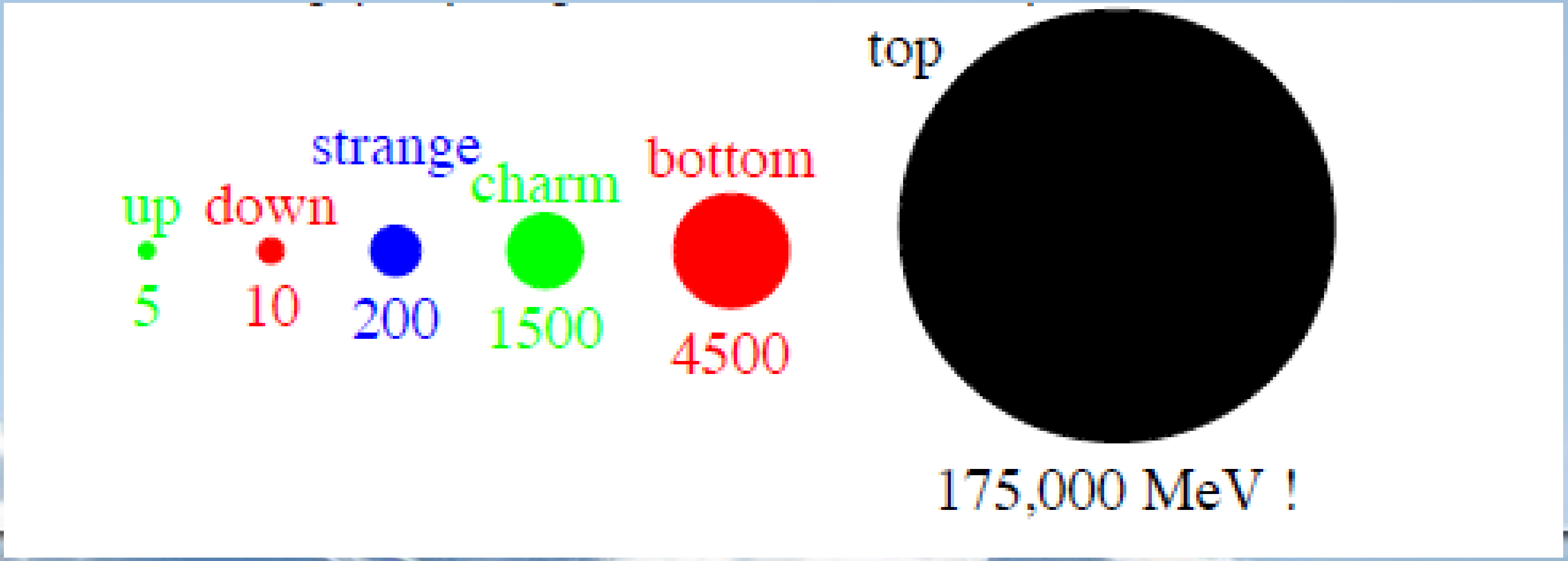
- What is the nature of the universe and what is it made of?
- What are matter, energy, space and time?
- How did we get here and where are we going?



Relations between the constituents

Ordinary matter is made up of up and down quarks and electrons.

What are the rest? The distinguishing feature is the mass.



The Three families only connected via weak interaction

Matter

Three families of *Quarks* and *Leptons, but m*atter around us made up of only first of the three families

At high energies, particles produced democratically, that is all three families are produced equally.

This was the how particles were made in the early universe, near the time of the big bang, BUT .....

We live in a world of particles. Where are the antiparticles? Answer: There was apparently a near cancellation where slightly more particles than antiparticles produced. The reasons are unknown, but leading ideas connect to CP violation and baryon instability.

The Forces in Nature

type	rel.strength	force carriers	acts on/in
Strong Force	1	Gluons g m = 0	Quarks Atomic Nucleus
Electro-magnet Force	~ 1/1000	Photon γ m = 0	Electric Charge Atoms, Chemistry
Weak Force	$\sim 10^{-5}$	W, Z Bosons m = 80 , 91 GeV	Leptons, Quarks Radioactive Decays (β-decay)
Gravitation	$\sim 10^{-38}$	Graviton m = 0	Mass, Energy

Force Carriers (Bosons) exchange interactions

Unification

Electricity and Magnetism

Maxwell (1873) Unification of Electricity and Magnetism

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

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

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

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

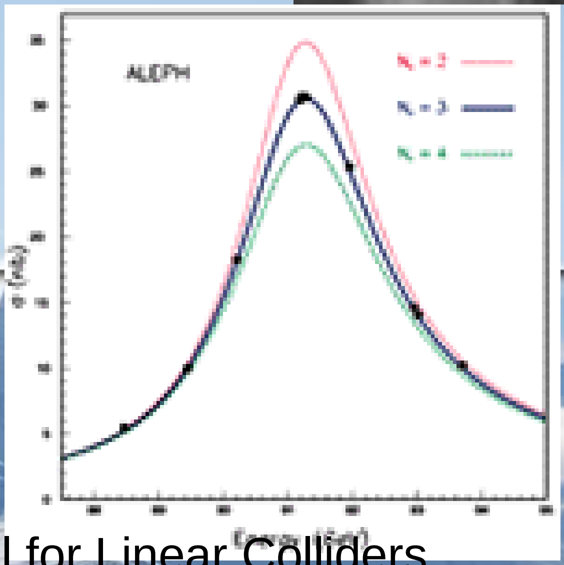
Triumph of the 19th century. Led to understanding of E&M form electromagnets to motors to modern devices like lasers

Further Unification
--- *Electroweak* ---

Proposed by Abdus Salam, Glashow & Weinberg

Key tests at LEP

In good agreement with all laboratory experiments

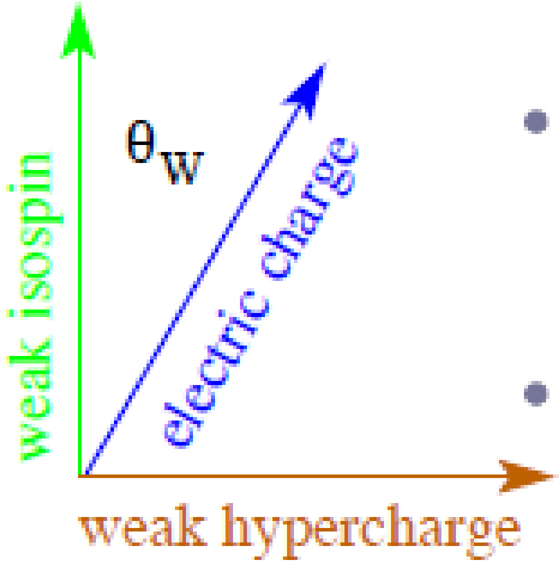


Electroweak Unification

"The standard model" of electroweak interactions
(Glashow, Weinberg, Salam)

Unification of Weak and Electromagnetic Forces

- SU(2) group: "weak isospin" ⇒ isotriplet of gauge bosons
- U(1) group: "weak hypercharge" ⇒ single gauge boson



- Weak isospin is quantum charge associated with Fermi's charge-carrying weak interaction
- Combination of weak isospin and weak hypercharge gives electro-magnetic interaction

Electroweak Unification

Parameters of unified theory (g, M_W, g') can be related to low energy parameters (e, G_F)

Let $g' \equiv g \tan\theta_W$; then:

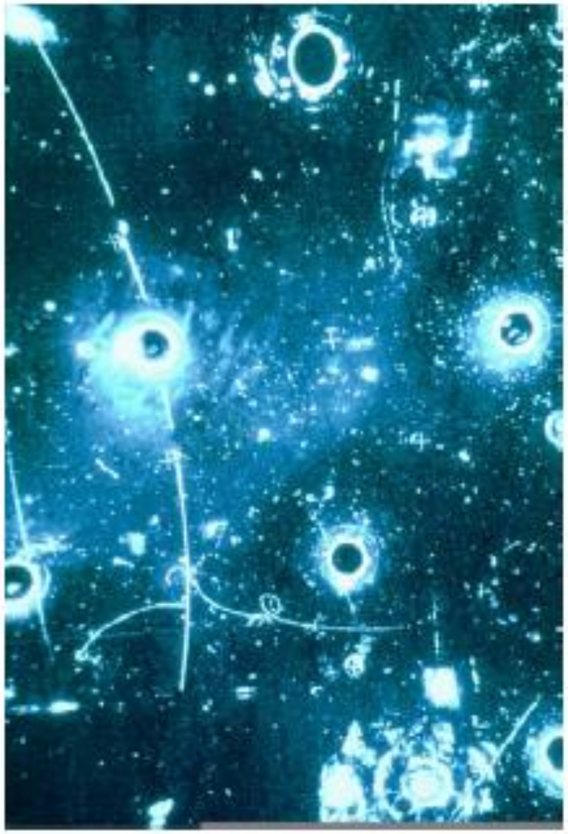
$$e = g \sin\theta_W,$$

$$G_F = \frac{g^2\sqrt{2}}{8{M_W}^2},$$

$$\frac{M_W}{M_Z} = \cos\theta_W$$

- Theory not only predicts a new weak interaction. . .
- But all of its properties follow from a single parameter, one of M_W, M_Z or θ_W

Experimental Proof

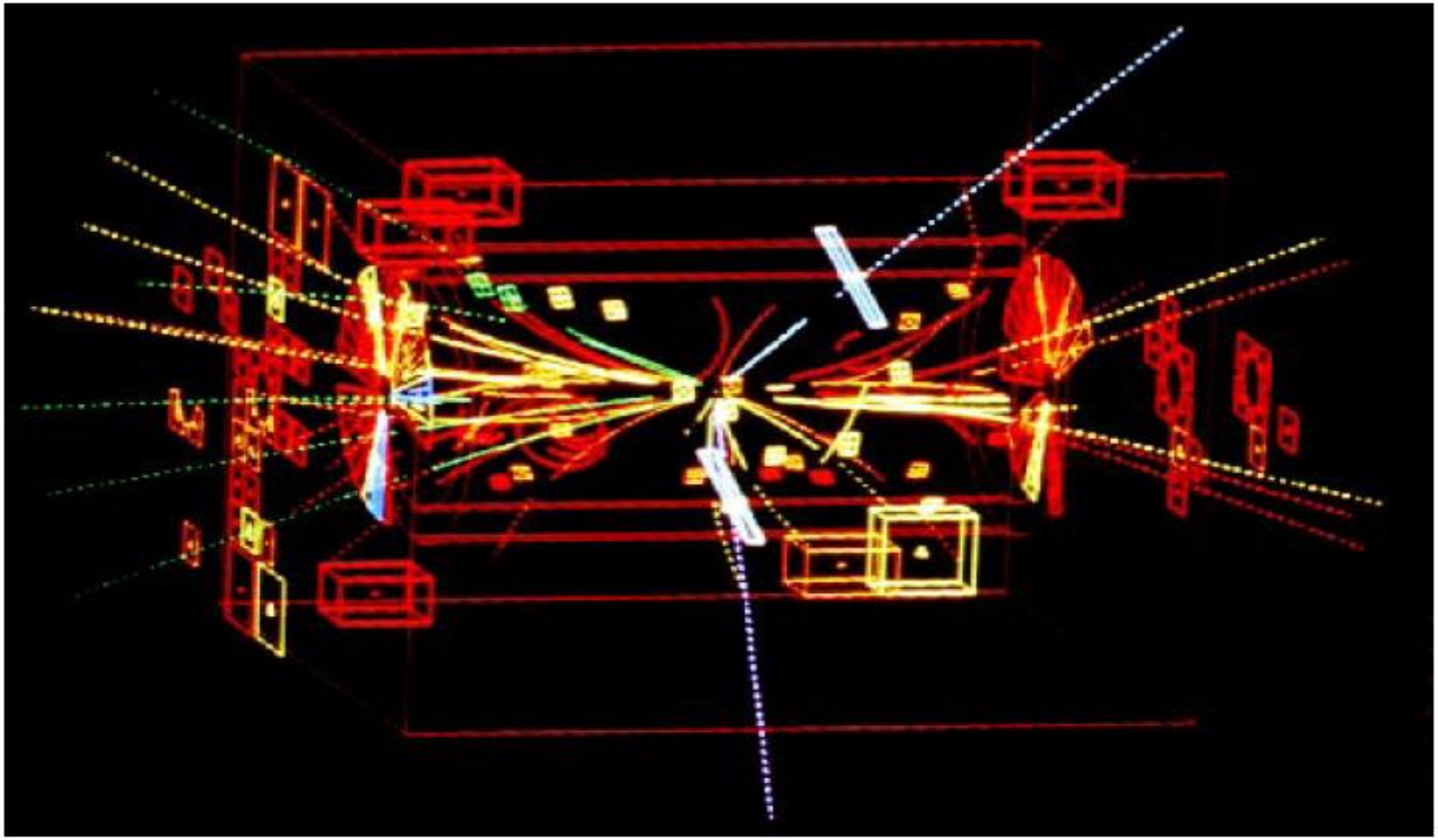


Discovery of the weak neutral current (1974)

ν + N → ν + Hadrons

Direct Confirmation

UA1 experiment at CERN $Sp\overline{p}S$ collider ($\sqrt{s} = 540$ GeV)



$M_W \approx 81$ GeV, $M_Z \approx 91$ GeV

Prediction of the Standard Model

$e^+e^- \longrightarrow Z^0 \longrightarrow f\,\bar{f}$

where $f=q,l,\nu$

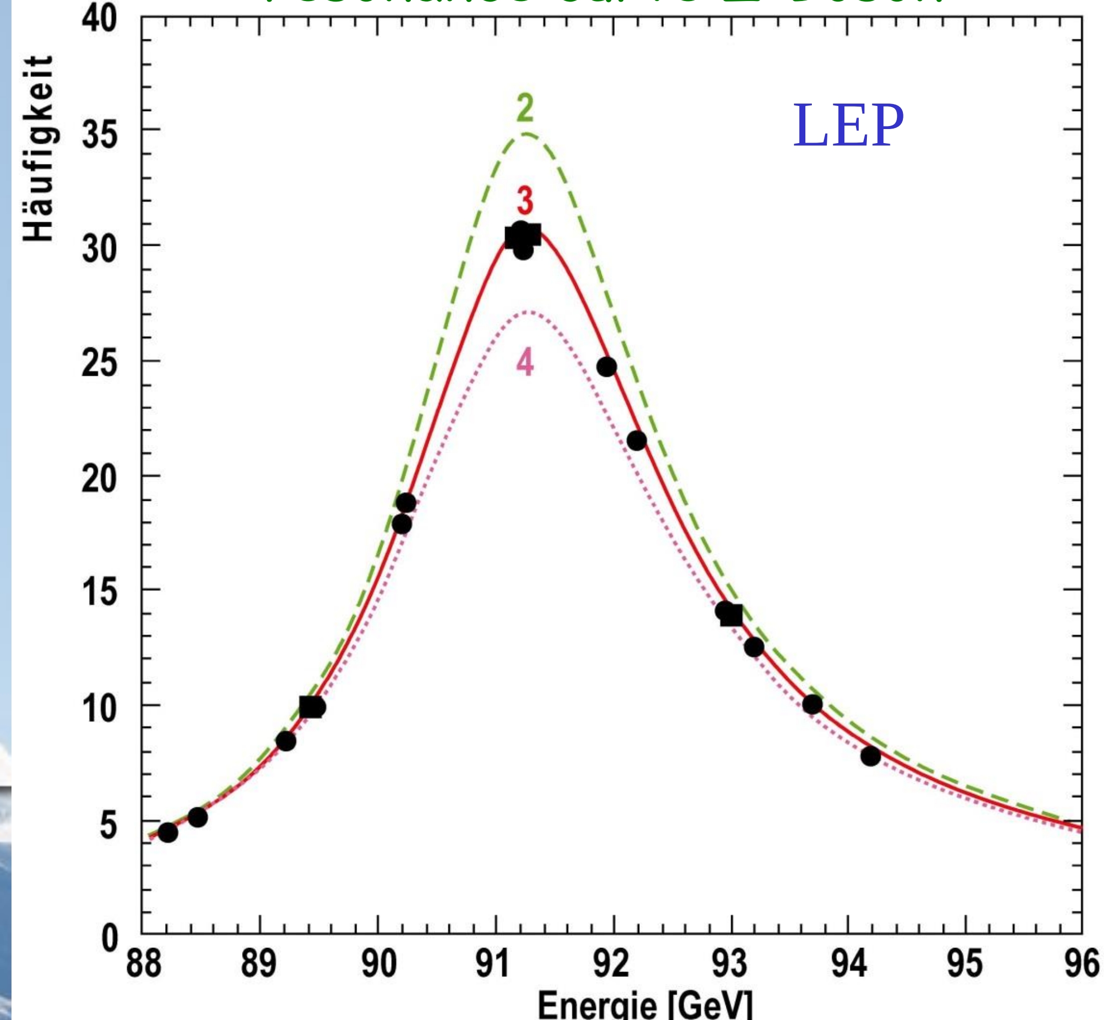
σ_Z and Γ_Z depend on number of (light) neutrinos

Number of families:

N = 2.984 +– 0.008

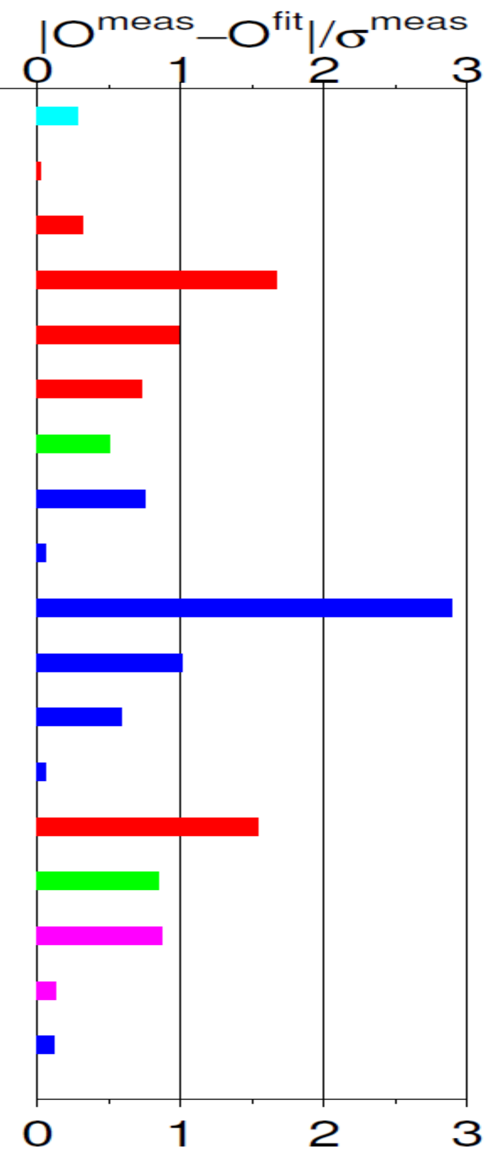
Nobel Prize 2008: Kobayashi-Maskawa)

resonance curve Z-Boson



LEP – Precision Tests of EW Model

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

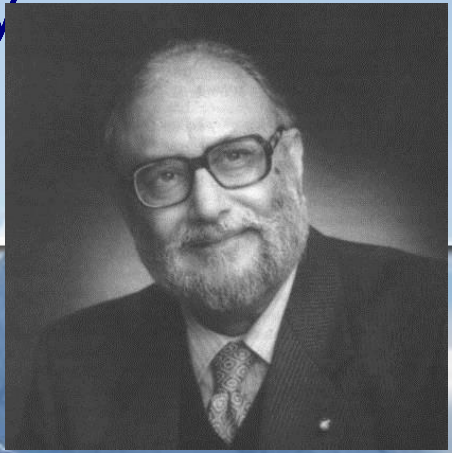
Unified Theory of Interactions

Maxell theory

Unification of electric and magnetic fields into electromagnetism

Weinberg-Salam model

- end of 1960’s
- Unify electromagnetic and weak interactions
- Introduced new particles Z^0, W^+, W^-
- They are discovered in 1983
- Advance of accelerator technology

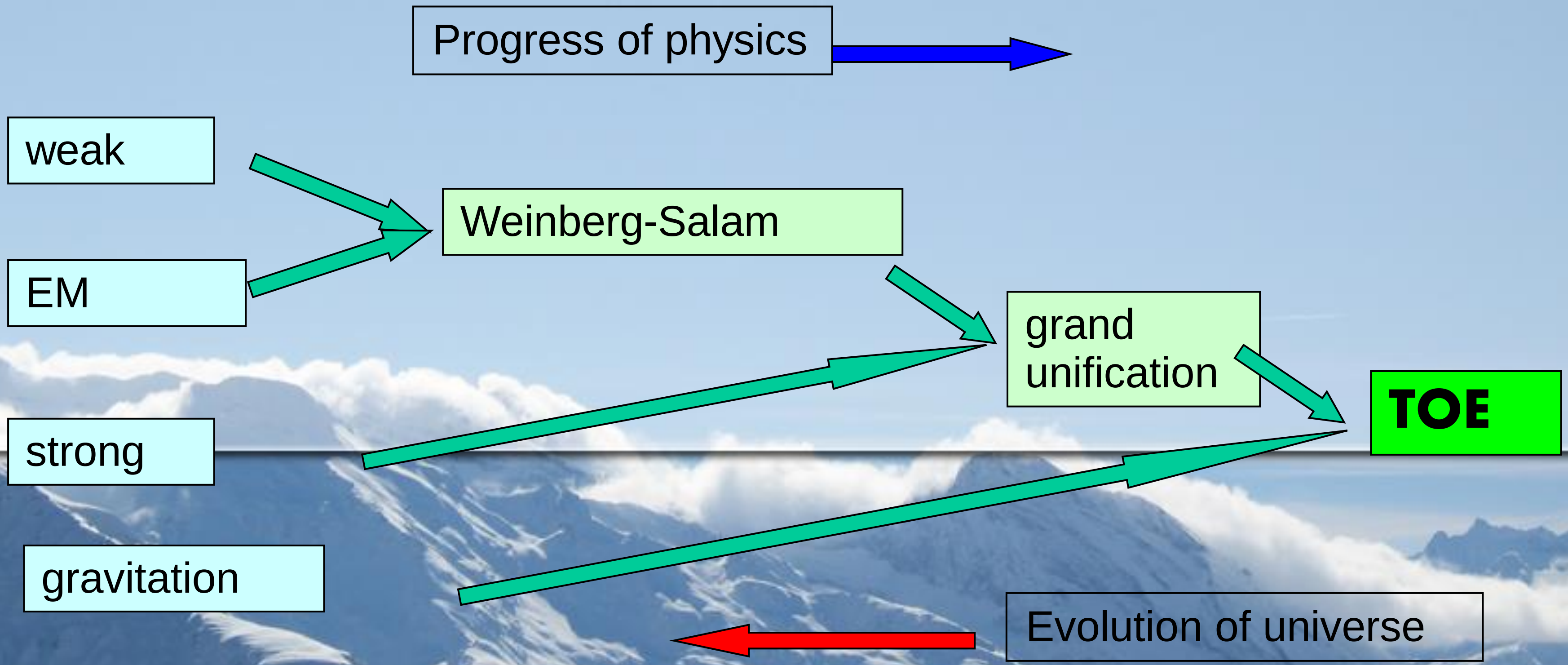


Next Step of Unification

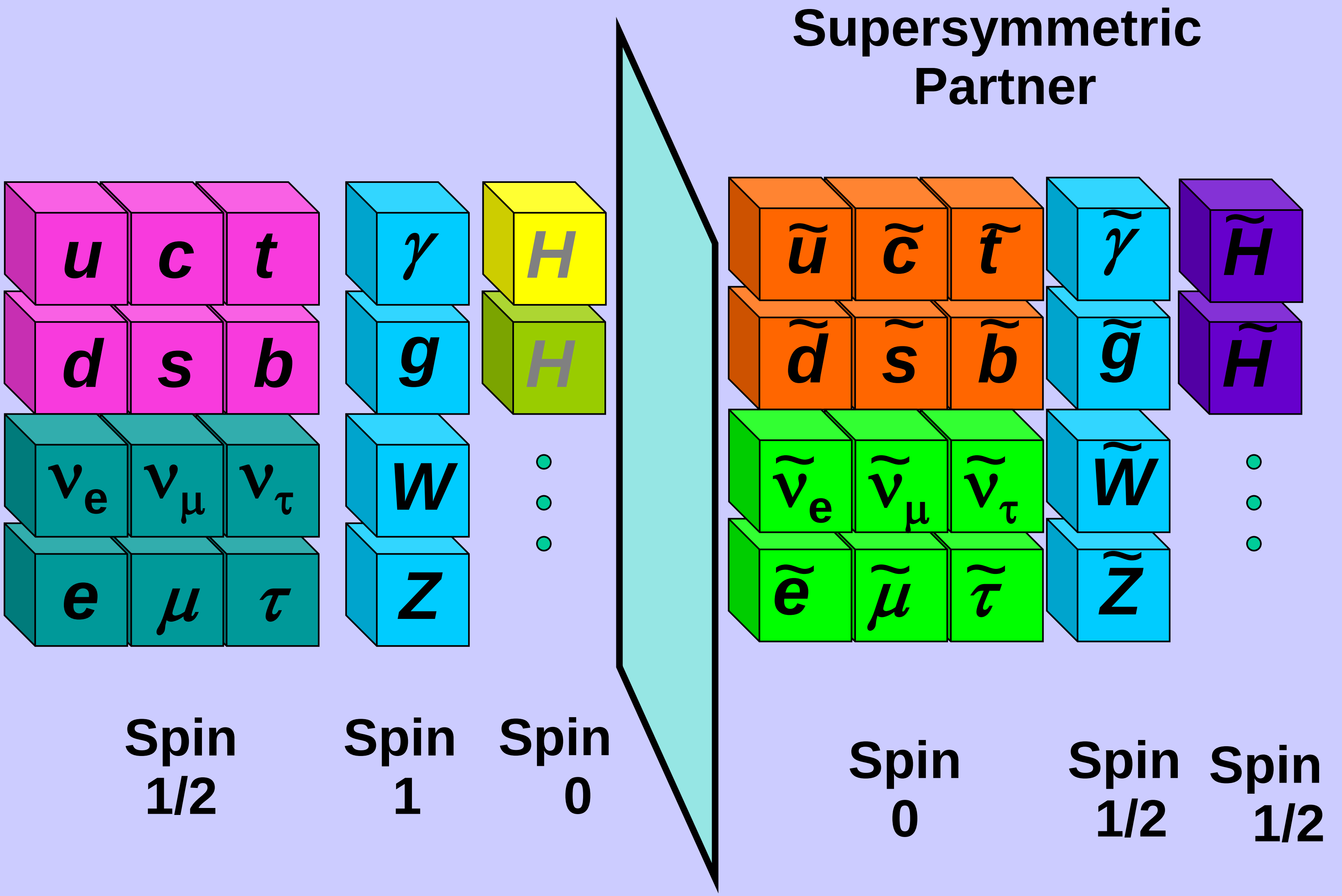
Unification of remaining 2 interactions

Further unification at higher energies

All forces be one at the beginning of universe?



Supersymmetry

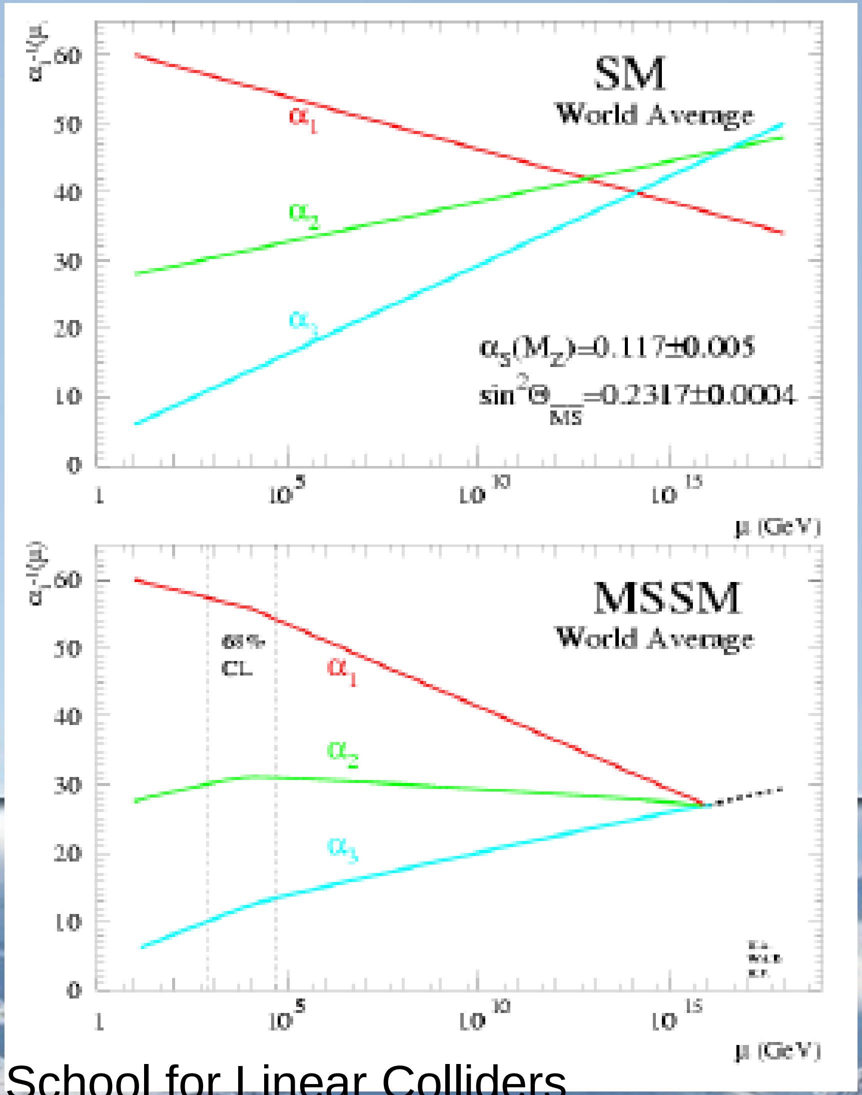


Is there a New Symmetry in Nature?

Bosons ⟷ **Fermions**

Integer Spin: 0, 1,..

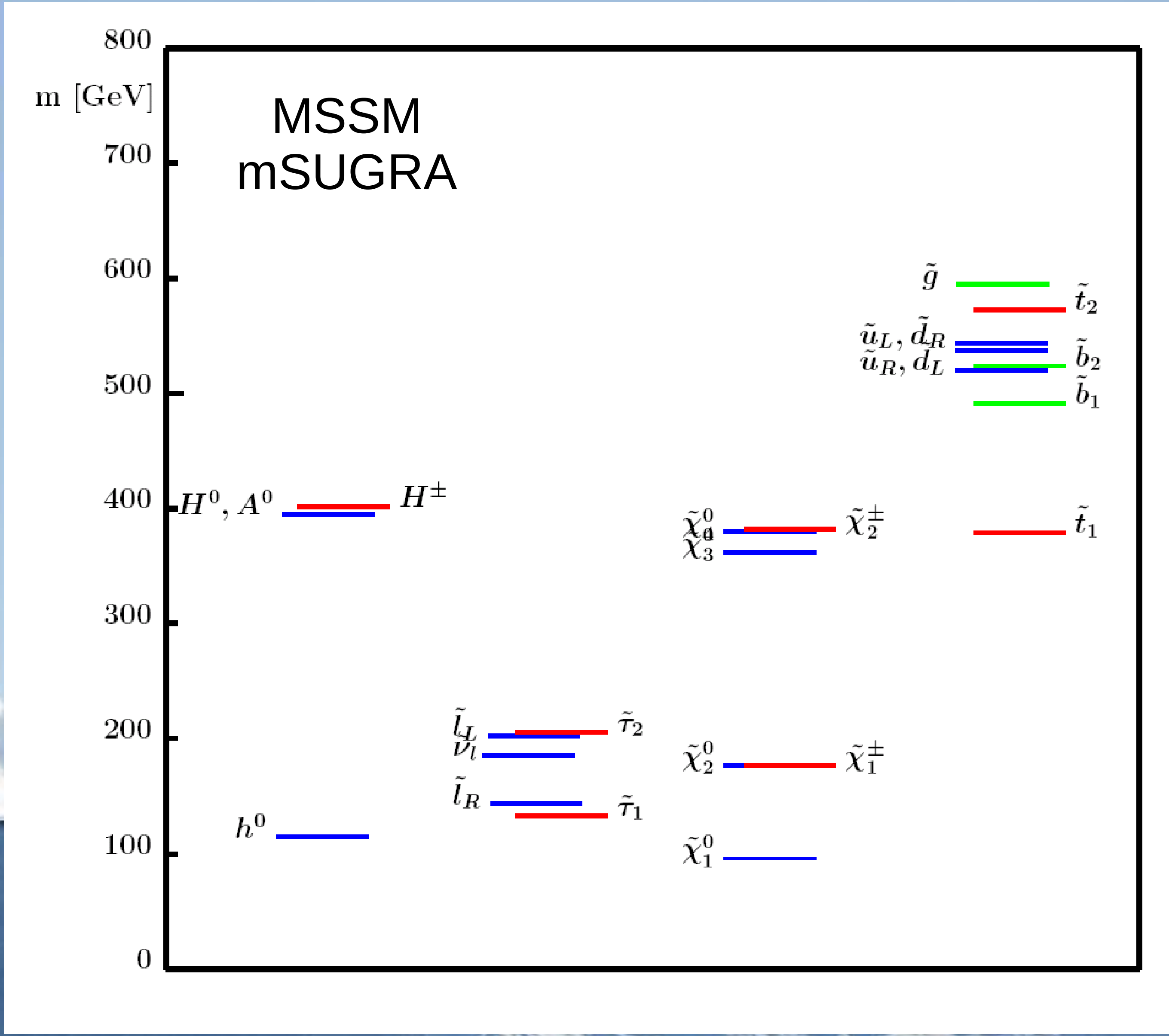
Half integer Spin: 1/2, 3/2,..



The virtues of Super-symmetry:

- **Unification of Forces**
- **The Hierarchy Problem**
- **Candidate for the Dark Matter**
- **…**

Spectrum of Supersymmetric Particles



squarks and sgluons heavy yielding long decay chains ending with LSP neutralino

Higgs Mechanism

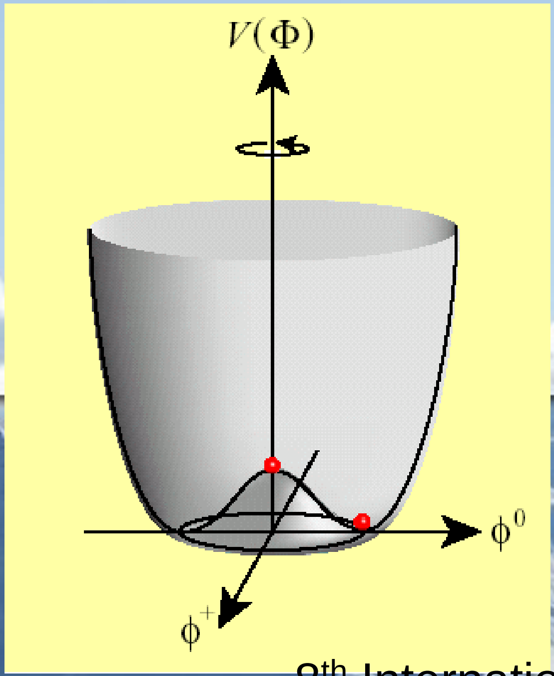
Higgs mechanism

- Application of Namu-Goldstone
- Starting with massless particles with symmetry
- Spontaneous symmetry breaking introduced by Higgs
- Can create mass of particles coupled to Higgs
- Applied to Weinberg-Salam

Higgs: the last member of the Standard Model

Y. Nambu

P. Higgs



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

$$<\phi> = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

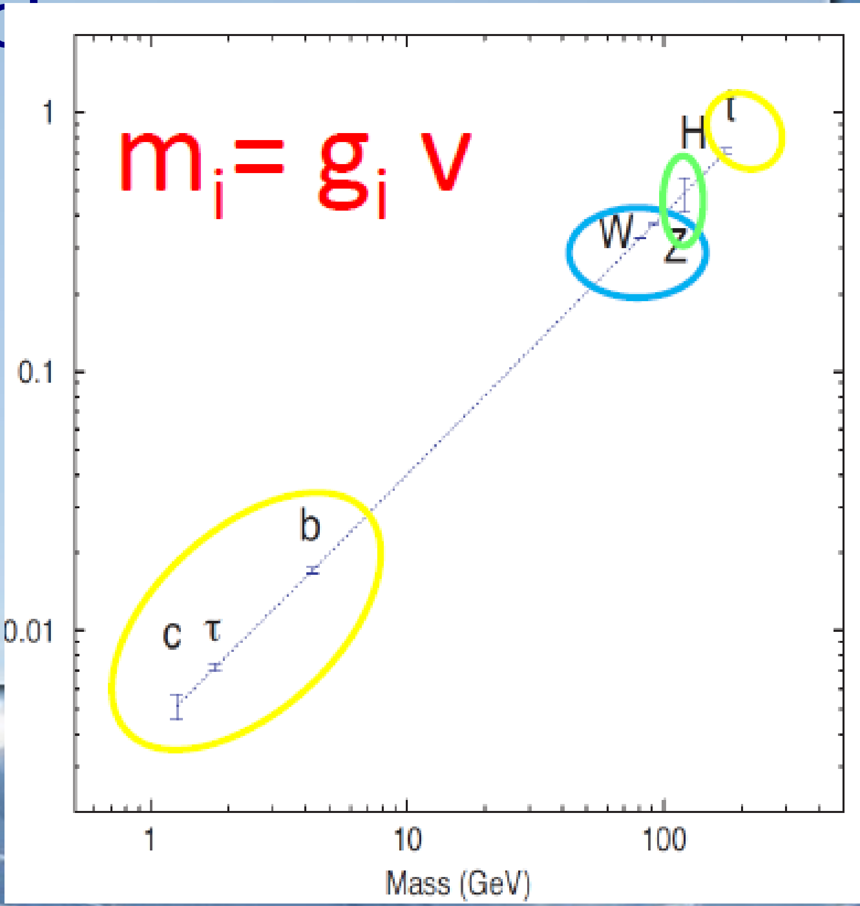
$$M_H = 2\lambda v^2$$

Properties of Higgs

Generate spontaneous breaking of electro-weak symmetry

Scalar field coupled to all partic

- Mass of all particles come from the coupling to Higgs
  - Coupling to gauge fields (Z, W, g)
  - Coupling to quark and lepton (Yukawa coupling)
  - Self-coupling
- All these must be confirmed



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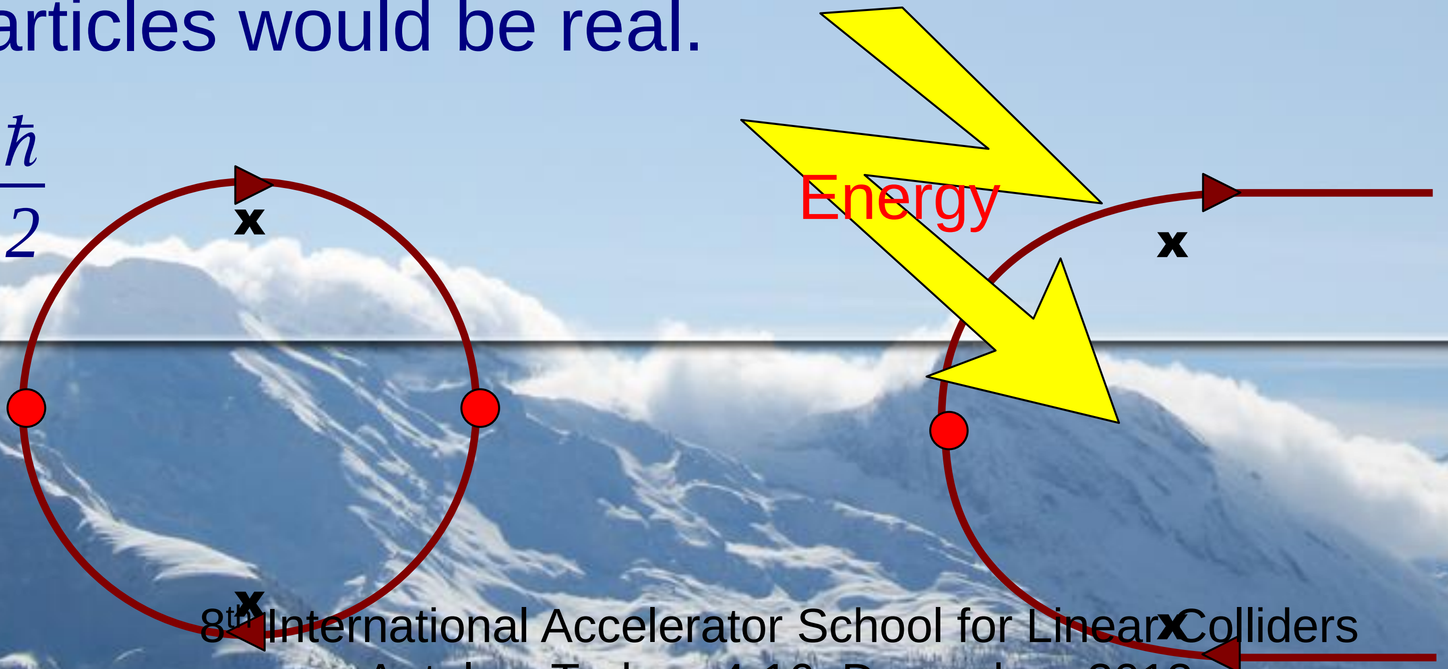
How to reach beyond the known scale.

- We have to find new phenomena which can not be understood with the current framework.
- Suggestion from quantum field theory：Vacuum may contains unknown particles.
- By giving energy to the vacuum, these virtual particles would be real.

$$\Delta E \Delta t > \frac{\hbar}{2}$$

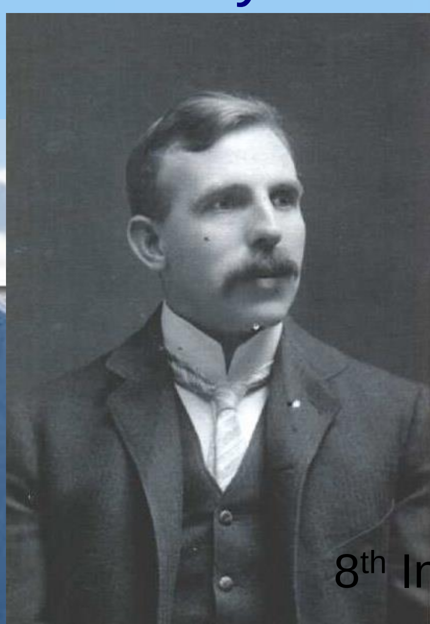


Another Example

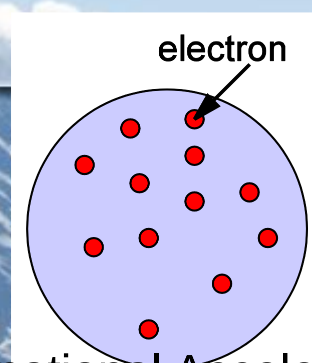
- According to quantum theory, spatial and momentum are

$$\Delta x \Delta p > \frac{\hbar}{2}$$

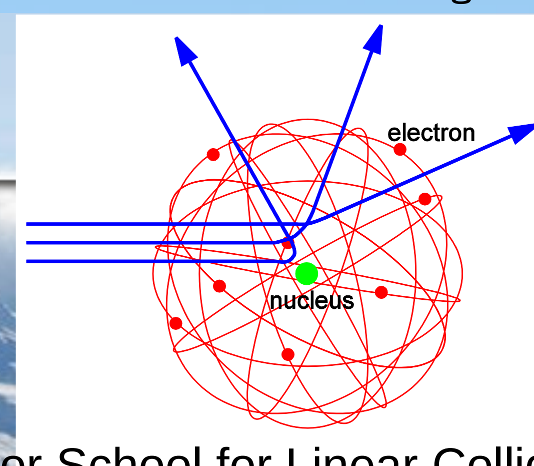
- Rutherford confirmed nucleus by alpha particle scattering with gold foil .
- The high momentum (small spatial resolution) of alpha particle is essential. If we employ visible light (a few hundred nm), we see only continuous object.



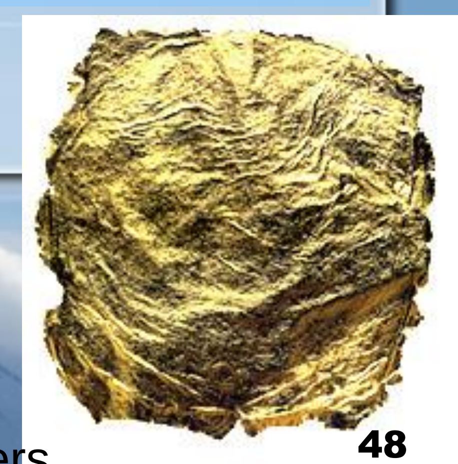
Charge cloud model



Rutherfor scattering



By visible light



Accelerator is useful

- Observing the nature with higher energy would cause new phenomena.
- Accelerator is a powerful tool to reach such region.
- Accelerator can boost up only charged particles with electric field.

$$d(\gamma mc^2) = \int q\left(\vec{E} + \frac{d\vec{s}}{dt} \times \vec{B}\right) d\vec{s}$$

Always zero

- Journey to the new frontier is supported by this principle.

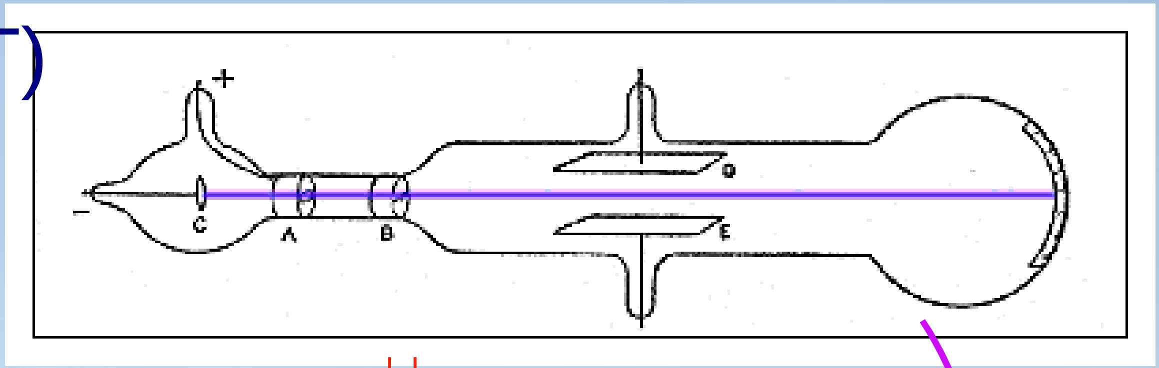
CRT: Cathode Ray Tube

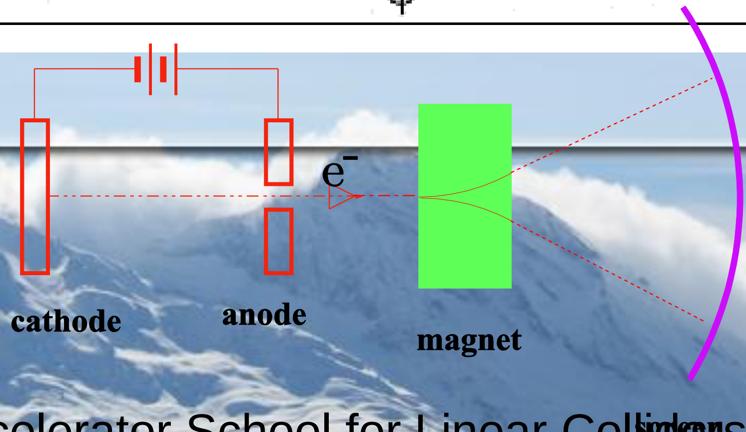
Electric voltage between two metallic plates

Heat the cathode --- something emitted

Proved the existence of electron in 1897 by J.J. Thompson

TV monitor (CRT)





Cock-Croft Electro-Static Accelerator

High voltage by static electricity

First nuclear transformation by accelerator

H + Li → 2 He

Cavendish institute in UK, 1932

800keV

Breakdown limit

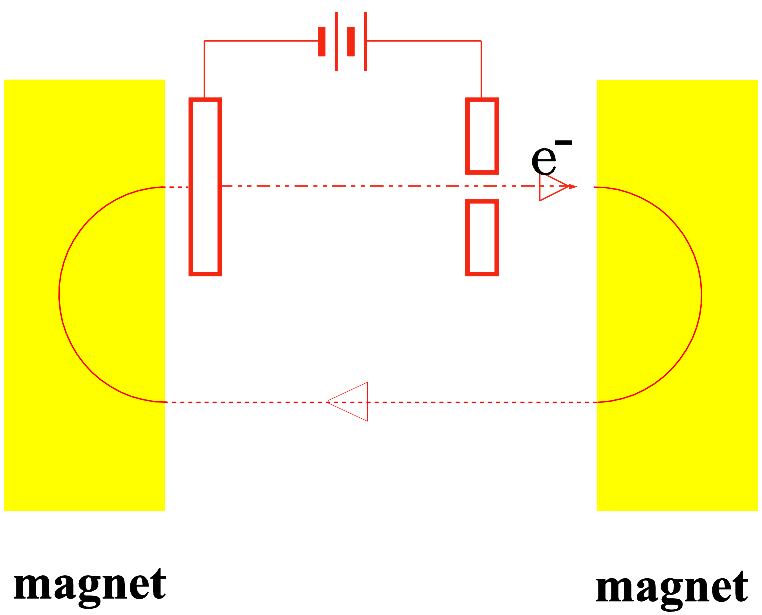
KEK 750keV Cockcroft-Walton

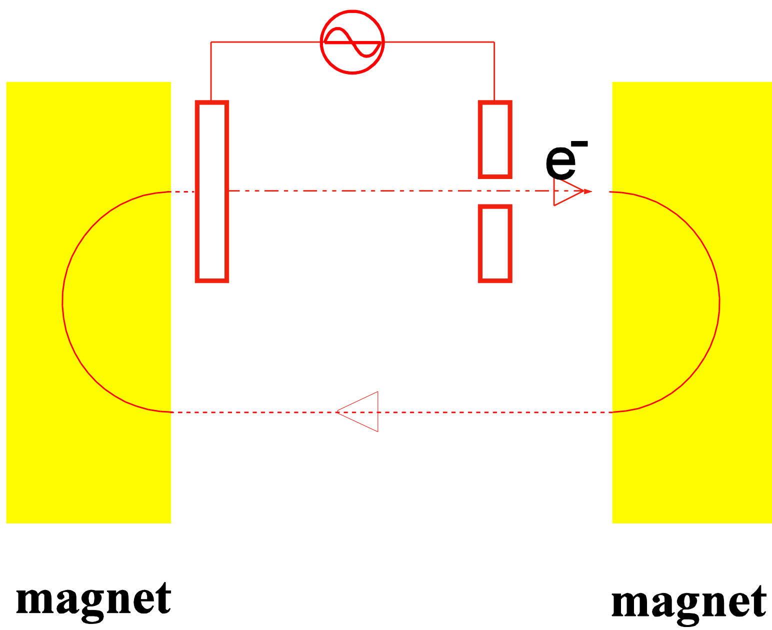
Repeated question: How can we go to higher energies?

reuse of CRT possible?

→

- use of alternating voltage
- high frequency needed

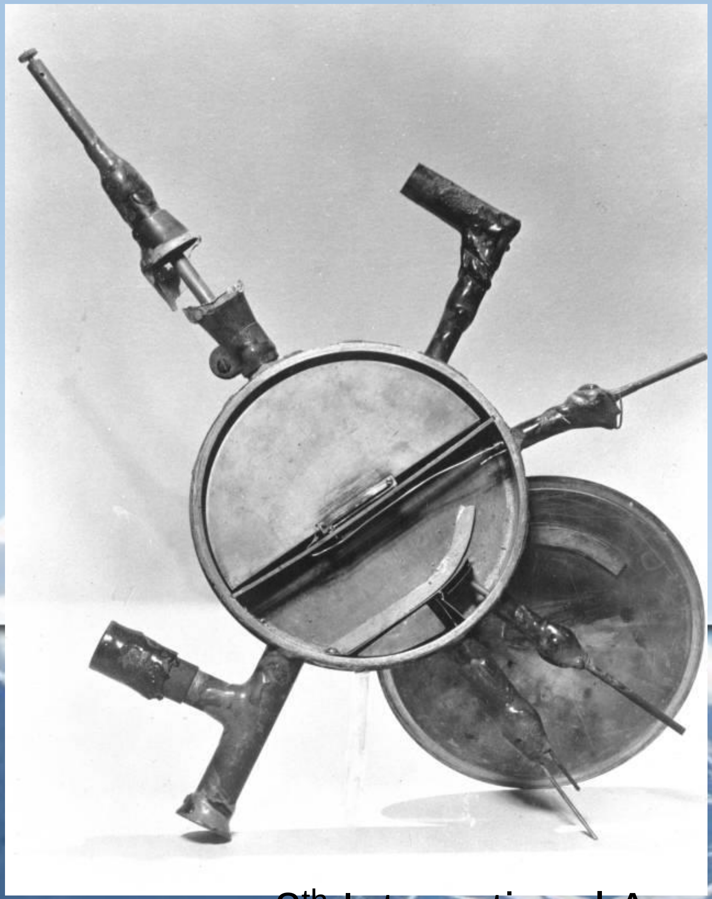




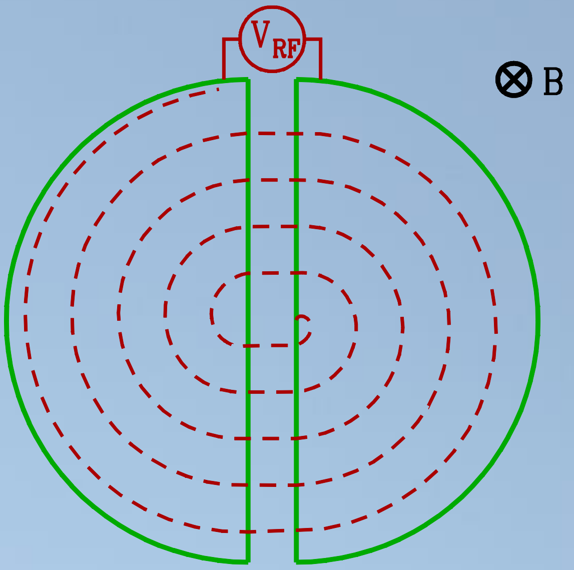
Cyclotron

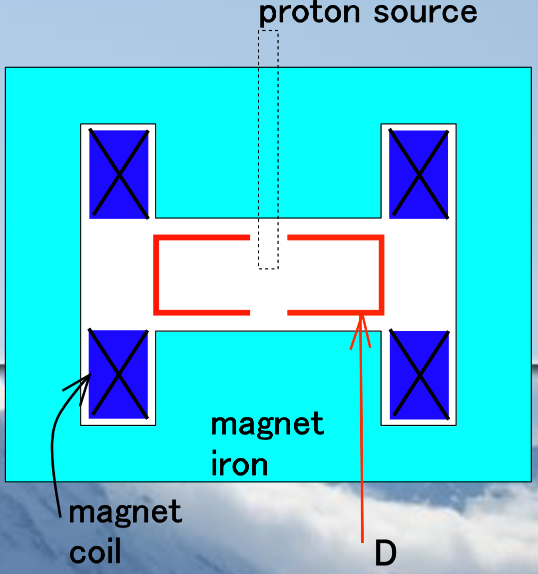
E.O.Lorence, 1931
Berkeley, California

Revolution period independent of energy



http://www.lbl.gov/image-gallery/

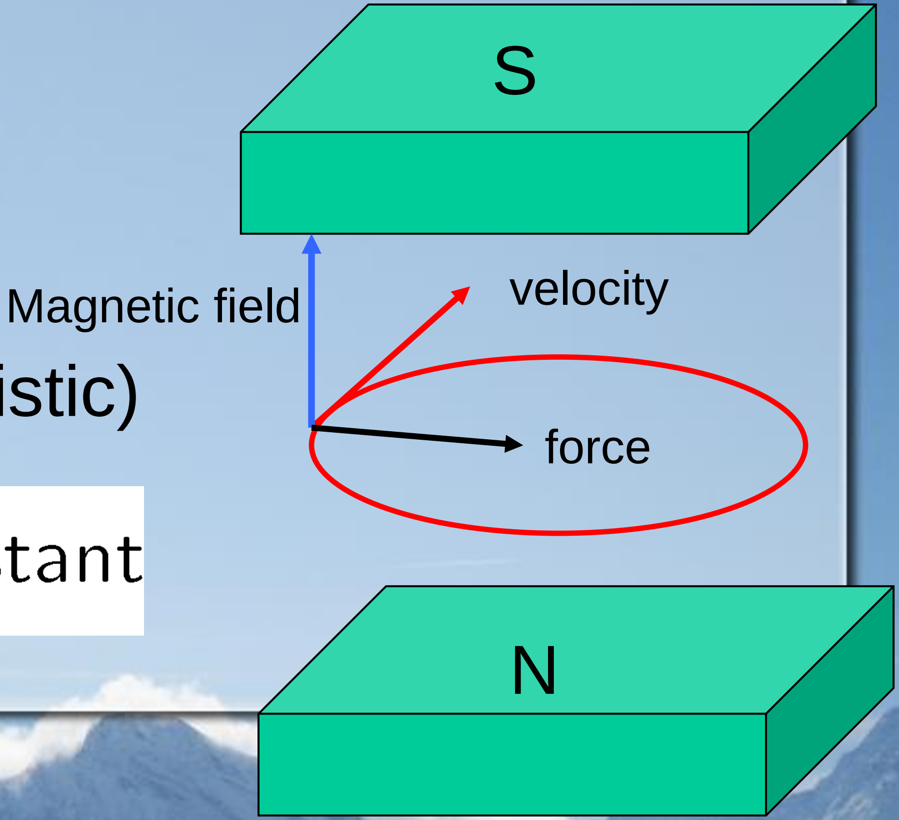




Relation : radius – magnetic field – beam energy – revolution time

Radius

$$\rho[\mathrm{m}] = \frac{p[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]}$$



- Revolution period (non-relativistic)

$$T = \frac{2\pi\rho}{v} = 2\pi\frac{m}{eB} = \mathrm{constant}$$

Limitation of cyclotron

Bigger and bigger magnets for higher energies

$$\rho[\mathrm{m}] = \frac{p[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]}$$

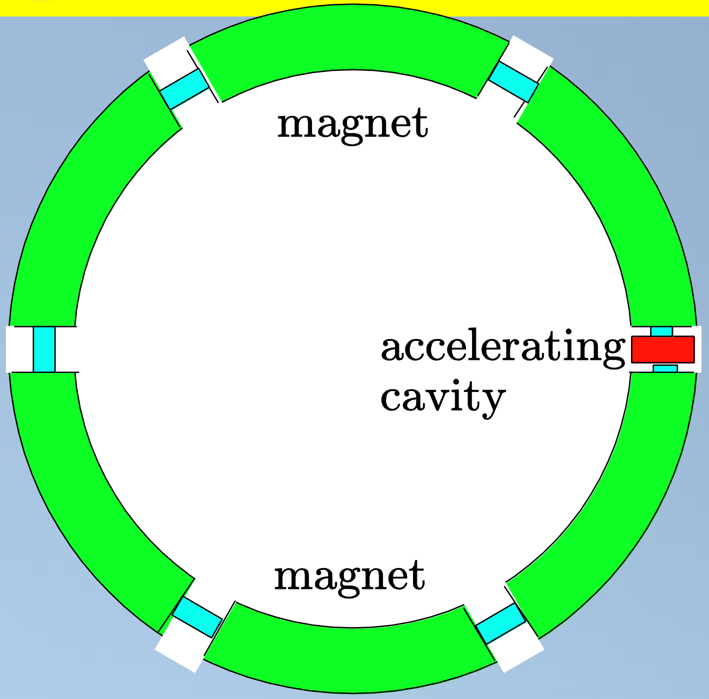
- Revolution time is not actually constant at high energies (special relativity) →
  - < 10 keV for electron
  - up to ~1GeV for proton

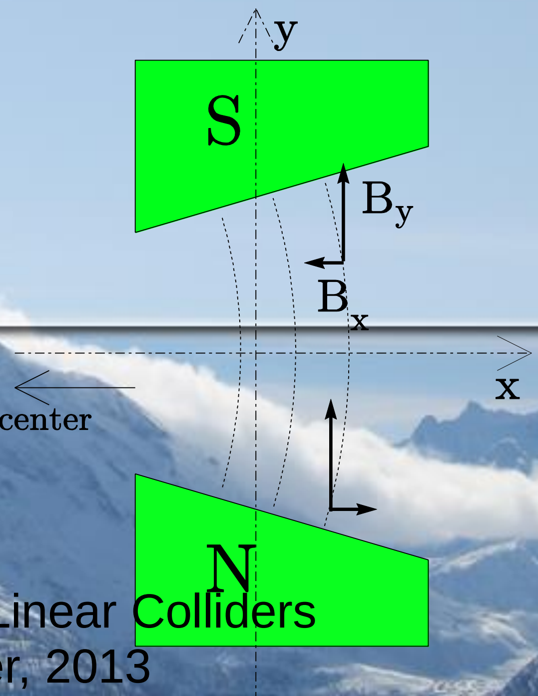
$$T = 2\pi \frac{m}{eB} \frac{1}{\sqrt{1-(v/c)^2}}$$

- Still being used at low energy physics
- advantage: continuous beam

Synchrotron

- Make orbit radius independent of energy
  - Raise magnetic field as acceleration
  - Save volume of magnets
  - Area of field is proportional to p (momentum), not p^2
- Gradient magnet needed for focusing
- Now main stream of circular accelerators





Particle Discoveries Before Accelerator Era

electron 1897

photon 1905

proton 1911

neutron 1932

----------------- Good Old Days --------------------

positron 1932

muon 1937

pion 1947

These (after neutron) are discovered using cosmic ray particles

New particle discoveries in 1950's by accelerators

1950's

A few GeV proton synchrotrons

- Cosmotron (BNL) 3GeV
- Bevatron (LBL) 6.2GeV

Many new particles

- anti-proton, anti-neutron
- Λ, Σ, Ξ, Ω,....
- Systematic description introducing "Quarks" by Gell-Mann in 1964

Bevatron

Weak-focusing synchrotron

Lorence Berkely Lab

Operation start in 1954

Bev.. = Billion Electron Volt
= Giga Electron Volt (GeV)

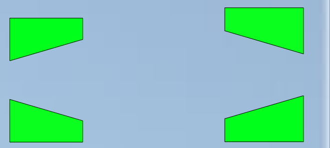
Up to 6.2 GeV

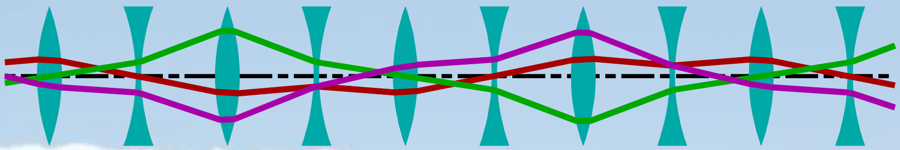
Discovered anti-proton in 1955

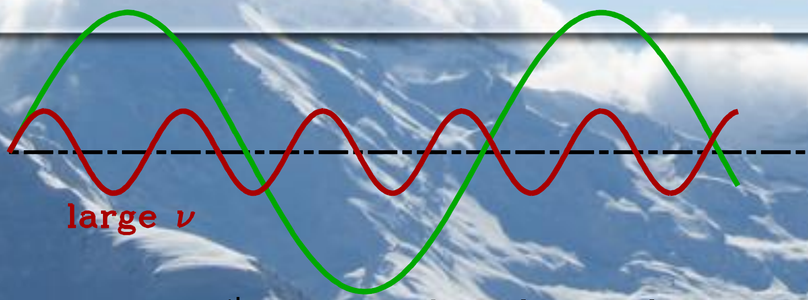
http://www.lbl.gov/image-gallery/image-library.html

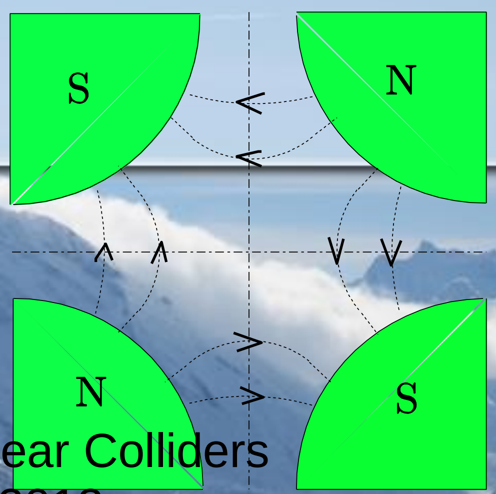
Principle of Strong Focusing

- Magnet size became an issue even for synchotron of a few GeV scale
- Combination of F-type magnet and D-type can reduce the beam size
- Around 1957
- Quadrupole magnets can also be used
- New issue: accuracy of field and alignment









AGS: Alternating Gradient Synchrotron

Synchrotron based on strong-focusing principle

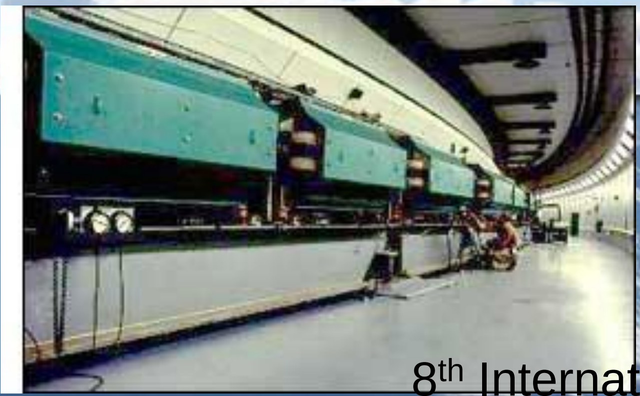
BNL in US

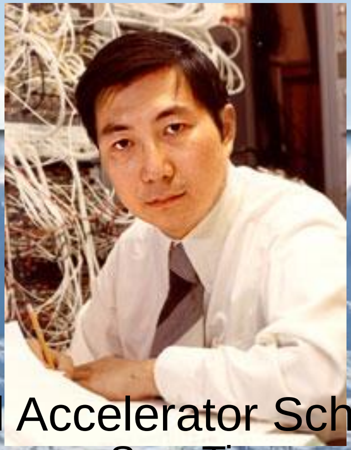
Operation start 1960, ~20GeV

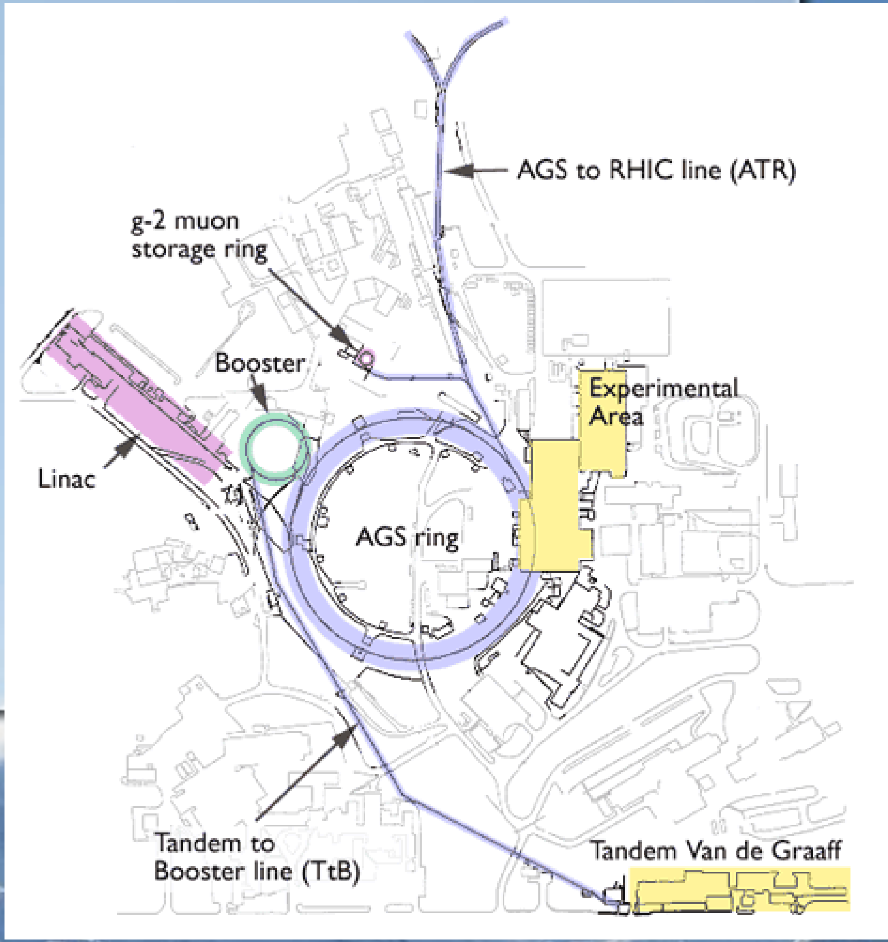
Up to ~33GeV

Discovered

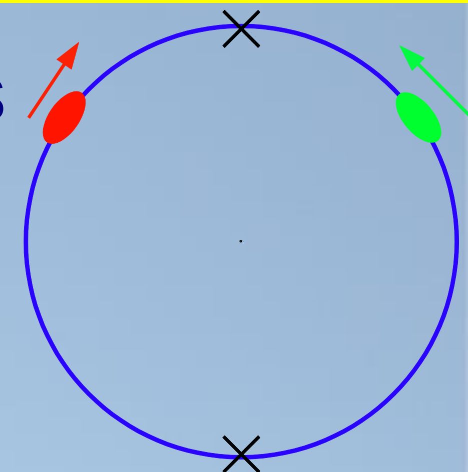
- J/ψ
- mu neutrino ν_μ







Storage Ring

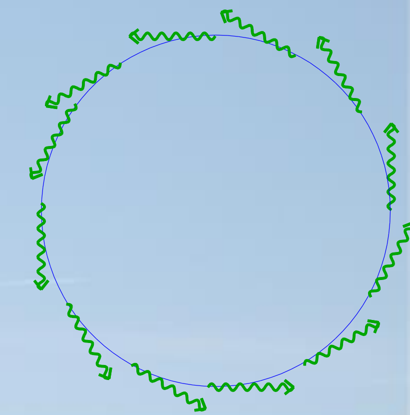


Synchrotron can be used to store beams for seconds to days

Usage

- Collider
- Synchrotron light source

Principle same as synchrotron but

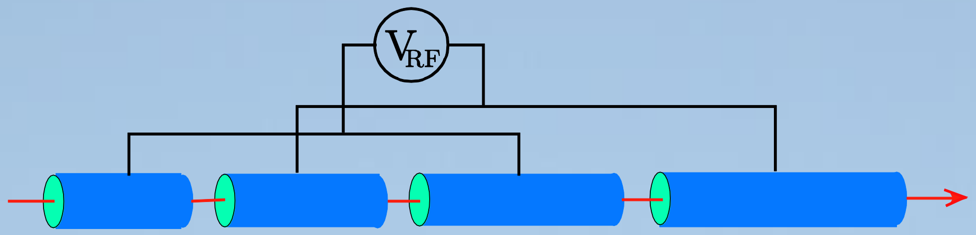


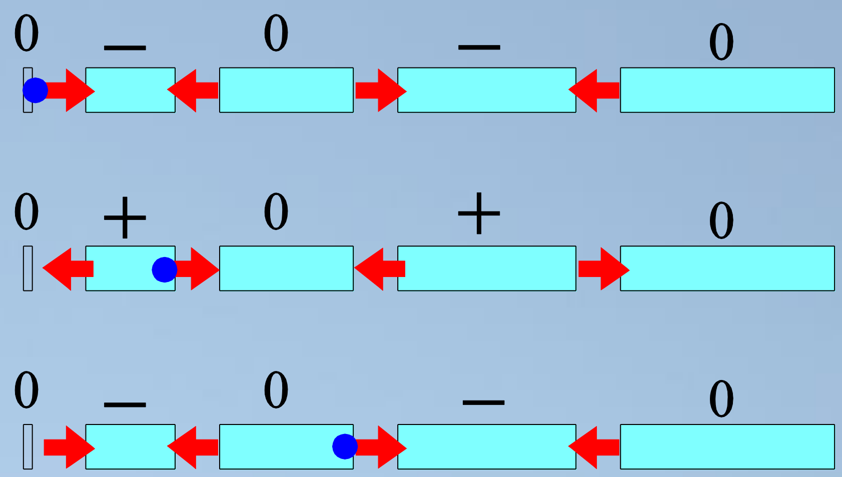
- no need of rapid acceleration (even no acceleration)
- longer beam life (e.g., better vacuum)
- insertion structure (colliding region, undulator, etc)

Linear Accelerator (Linac)

Drift tube type

The principle is old





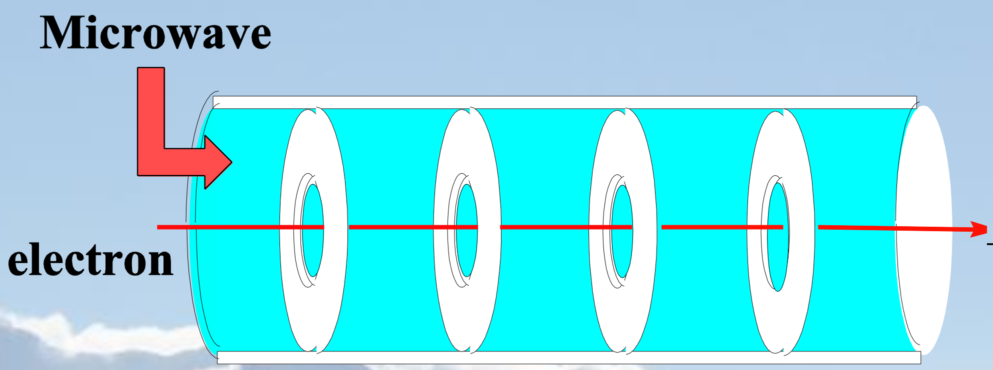
- The progress of microwave technology during World War II
- Application to accelerator after WW II

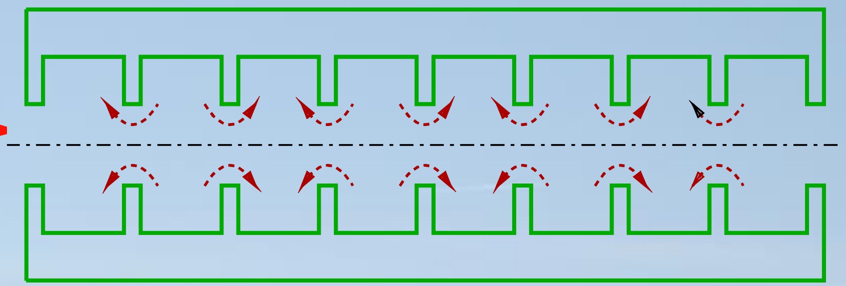
Electron Linac

Velocity is almost constant above MeV

No need of changing tube length

Resonator type

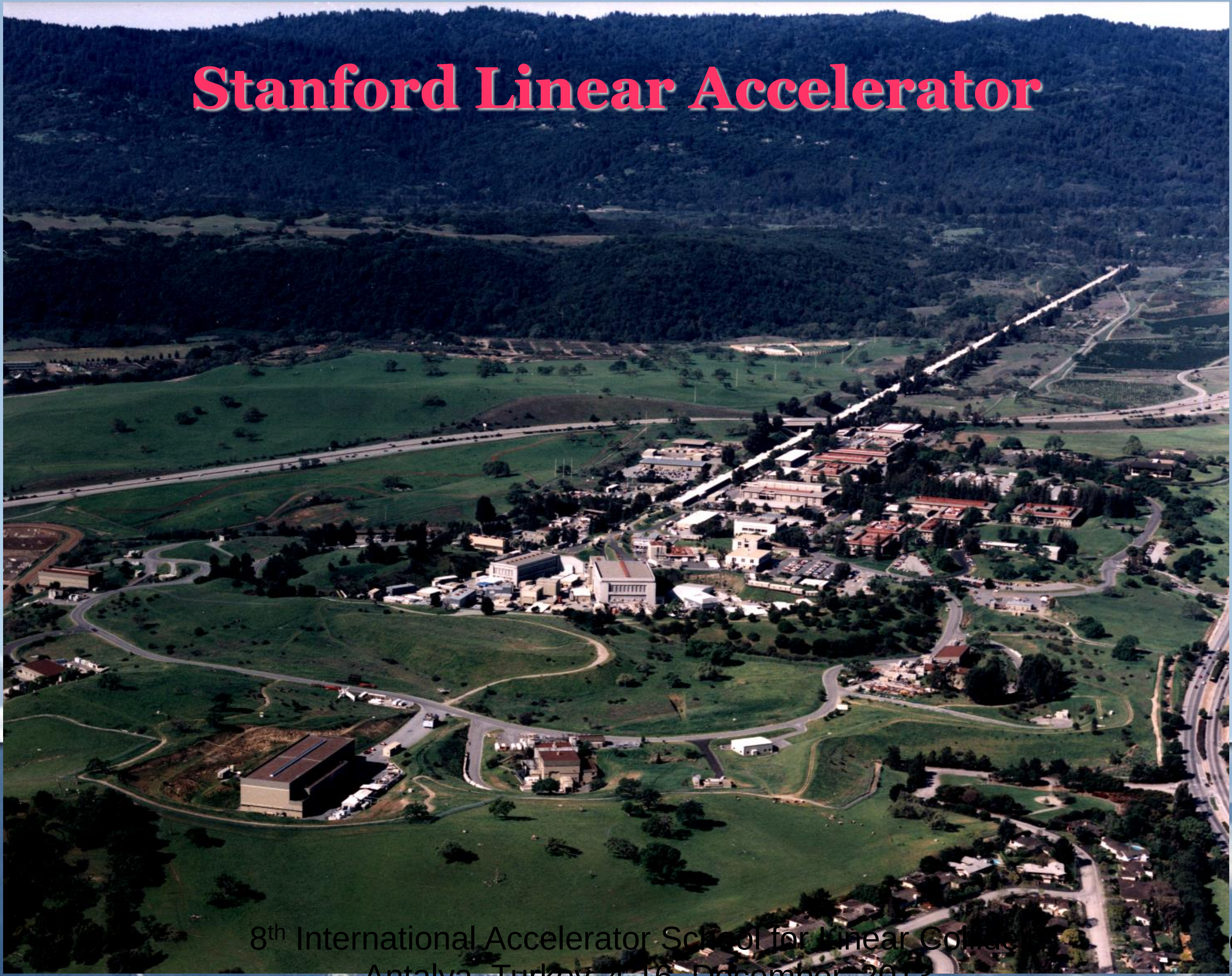




SLAC: Stanford Linear Accelerator

- Electron Linear Accelerator, 2 miles
- Microwave frequency 2856MHz (wavelength 10.5cm)
- Operation start in 1967
- Study of deep inelastic scattering (to probe proton structure by electron-proton scattering) in ~1968
- Maximum energy ~50GeV (since 1989)
- Still now the longest and highest energy electron linac
- Still an active accelerator, SPEAR, PEPII, SLC, LCLS, ...

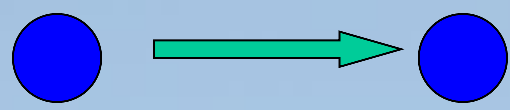
Stanford Linear Accelerator



Collider

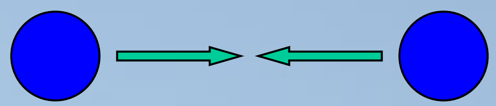
What matters in physics is the Center-of-Mass energy

Fixed target



$$E_{CM} \approx \sqrt{2Em}$$

Collider



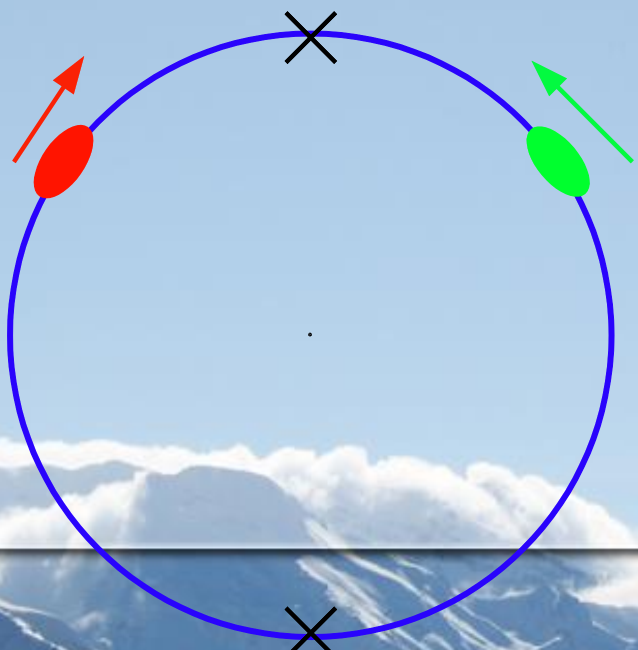
$$E_{CM} \approx 2E$$

- Energy of each beam can be lower in colliding scheme for given E_{CM}
- Colliding scheme much better in relativistic regime
  - e.g., for electrons, collision of 1GeV electrons is equivalent to 1TeV electron on sitting electron

How to Collide

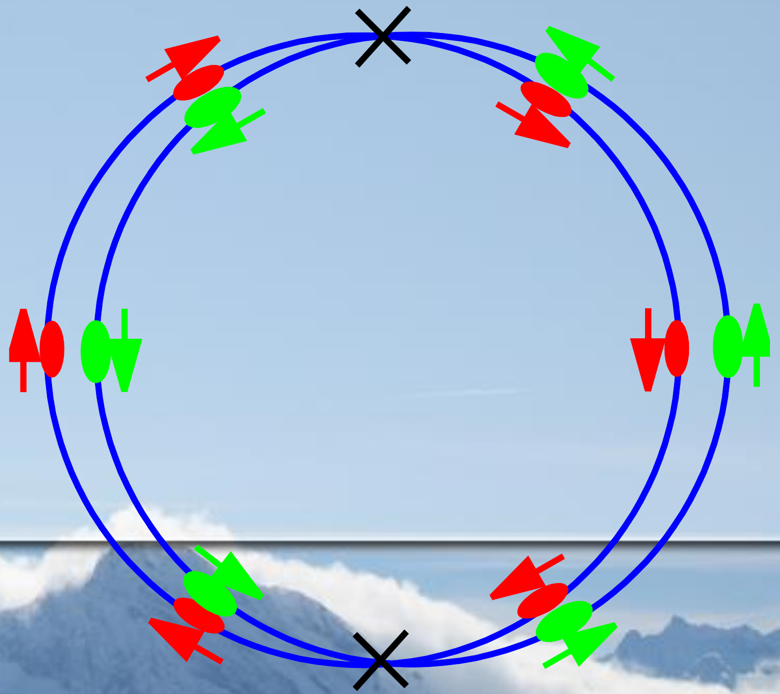
Can be done in one ring for same energy beams and opposite charge (e.g., e+e-, proton-antiproton)

- More freedom with two rings



.... PETRA, TRISTAN, LEP,

..... Spps, Tevatron



PEPII, KEKB, LHC, ...

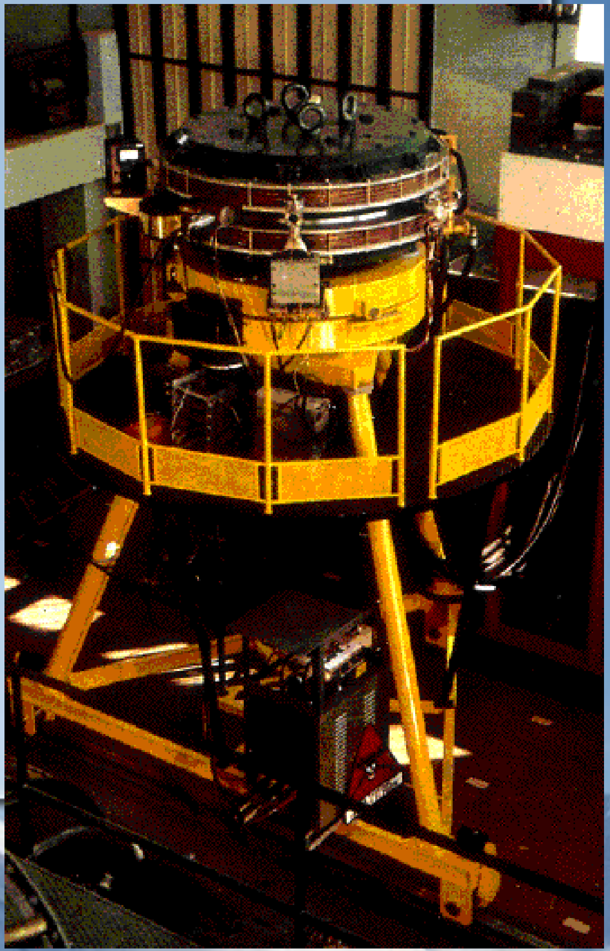
The First Electron-Positron Collider: AdA

First beam in 1961 in Italy

Moved to Orsay, France

The first beam collision in 1964

Orbit radius 65cm, collision energy 0.5GeV



Now in the garden

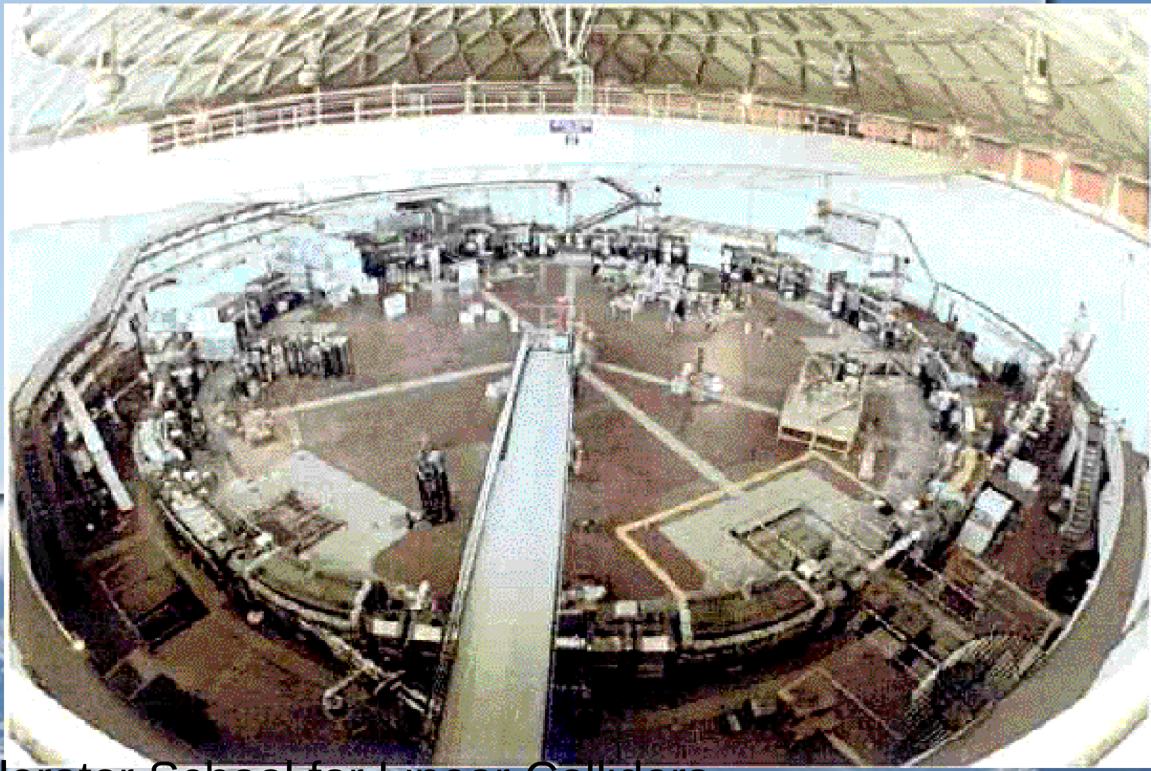
The Second one : Adone

First beam in 1967

Circumference 105m

Collision energy < 3GeV
(Unlucky, did not reach J/ψ at 3.1GeV !!)

Luminosity
3×10^{29} /cm^2/s



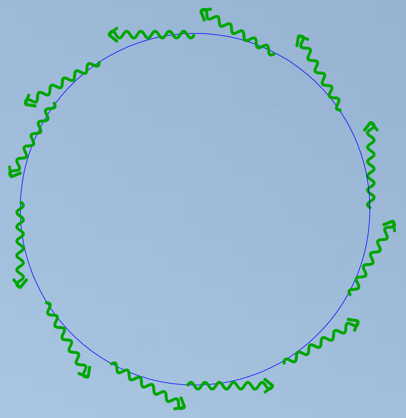
Synchrotron Radiation

Charged particles lose energy by synchrotron radiation

proportional to $1/m^4$

Loss per turn (electron)

$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$



- Not only unwelcomed effects but
  - can be used as light source
  - radiation damping → Damping Ring lecture

Maximum Energy of Collider Ring

Proton/antiproton

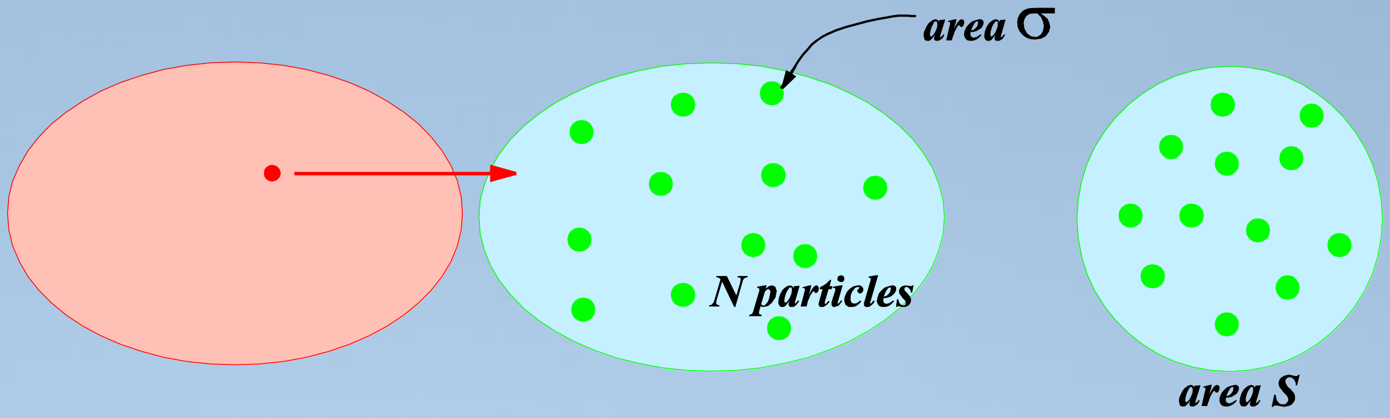
- Ring size
- Magnetic field

Electron/positron

- Ring size
- Synchrotron radiation
  - Electric power consumption

Luminosity

- Colliders can reach higher energies compared with fixed target
- But issue is the event rate



$$\text{Number of events/sec} = \mathcal{L}\sigma$$

$$\mathcal{L} = f_{collision}\frac{N^2}{S}$$

For Gaussian beams

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^*\sigma_y^*}$$

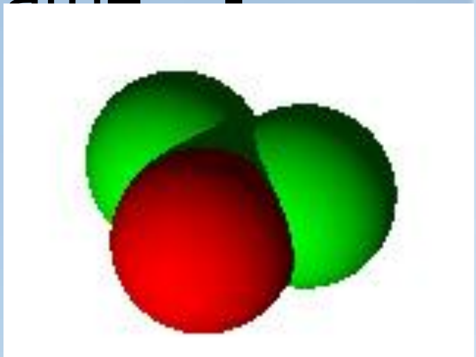
Colliders demand small beams

Quark Model: Gell-Mann, Zweig 1964

p charge=1
n charge=0
Λ charge=0

u quark charge = 2/3
d quark charge=-1/3
s quark charge = -1/3

p = u + u + d charge = 2/3 + 2/3 – 1/3 =
n = u + d + d charge = 2/3 -1/3 -1/3 = 0



Is this just mathematical model?

- I thought so when I was a college student (by Prof. Yokoya)

Quark is “observed” at SLAC, late 1960’s

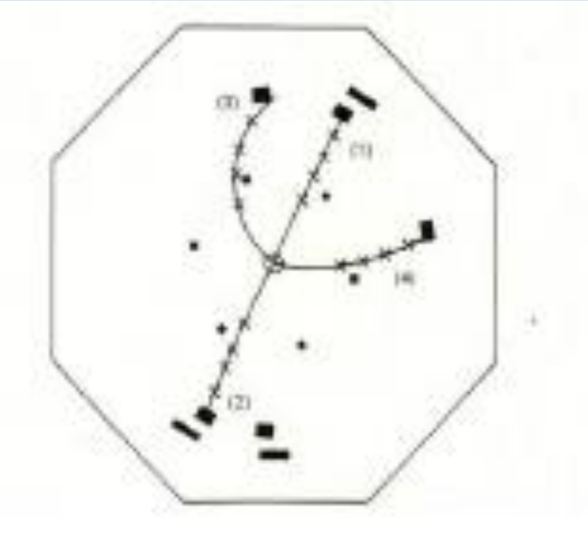
Charm Quark

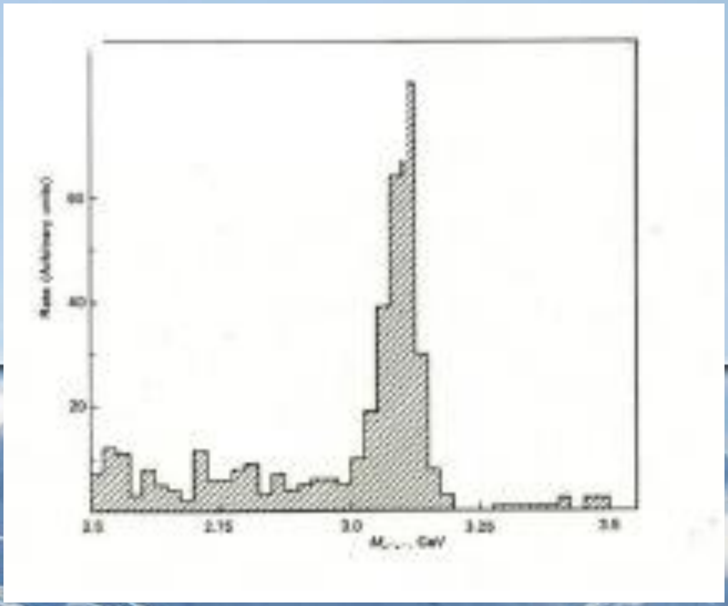
Discovery of J/ψ in 1974

$e^+e^- \rightarrow \psi$ at SLAC (Richter et.al.)

$J \rightarrow e^+e^-$ at BNL (Ting et.al.)

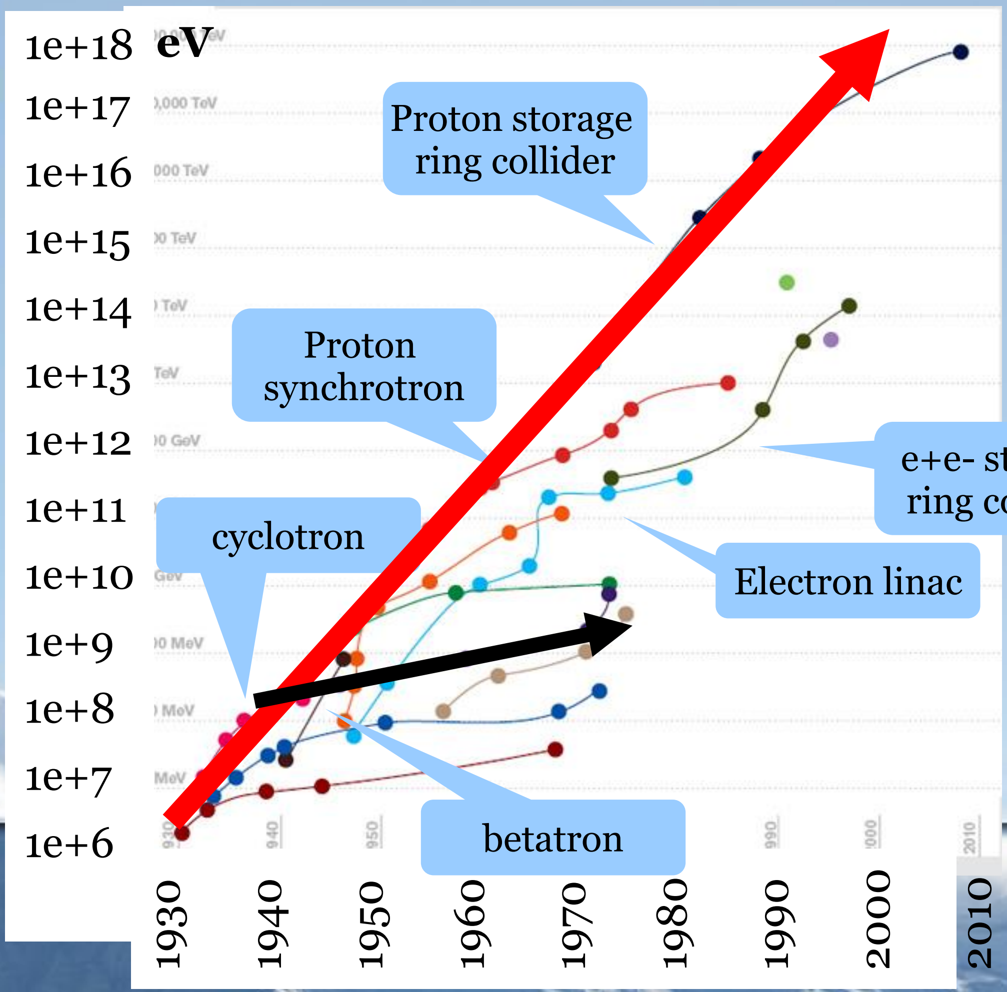
J/ψ = bound state of $c\bar{c}$





1. Driving force of Science
2. Our universe
3. Accelerator, another driving force
4. **Journey to the new world**

Livingston Plot :
Moore's law in accelerator



- Very rapid progress on the accelerator energy.
- It is kept by inventions.
- We need evolutions to keep going.

Multi-stage rocket!

From Symmetry Magazine

What is Collider?

- Center of Mass Energy depend on frame, even the beam energy is same.
- Collider : Maximize CME with a beam energy.

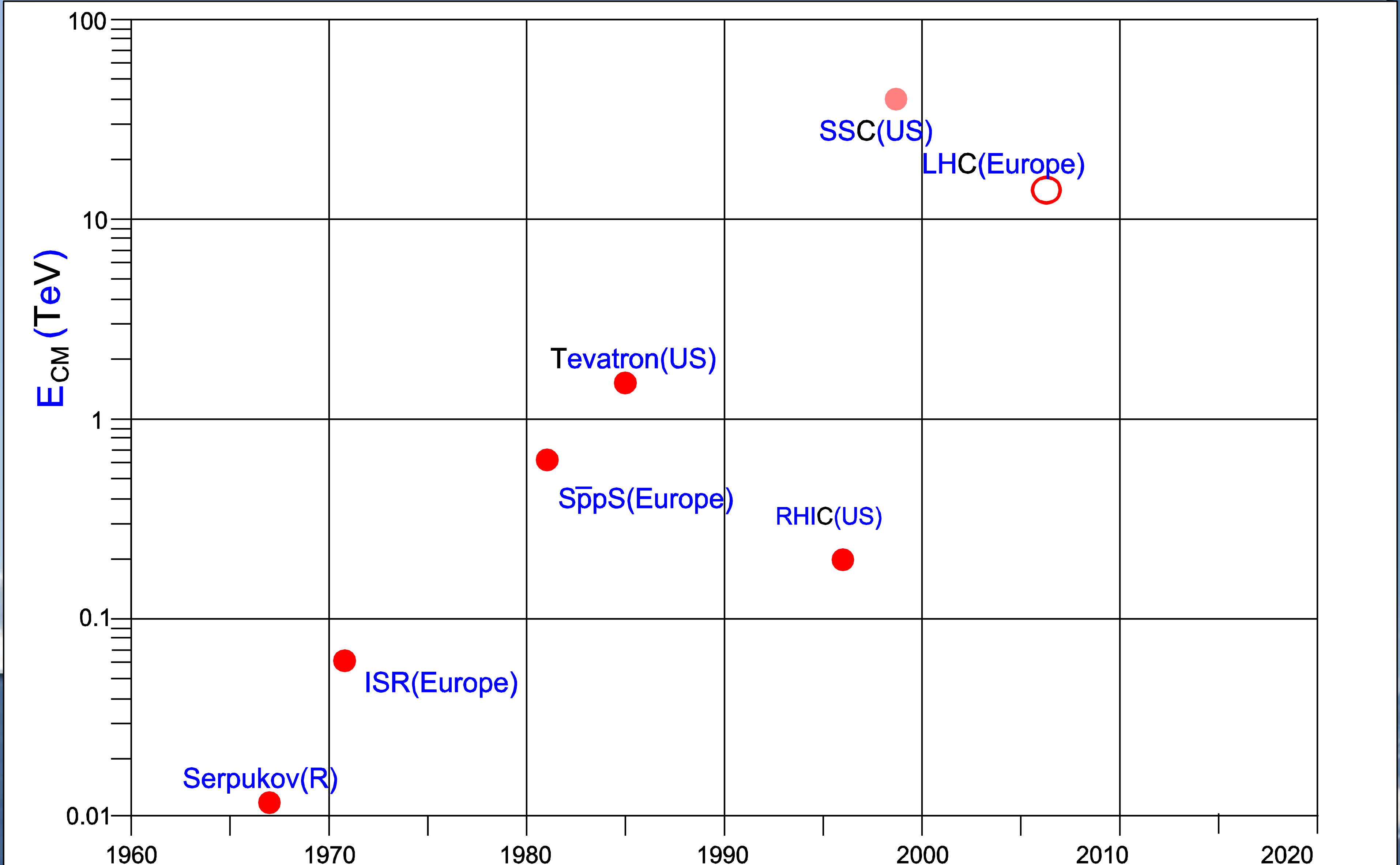
Fixed target

$$E_{CME} = \sqrt{2mE}$$

Collider

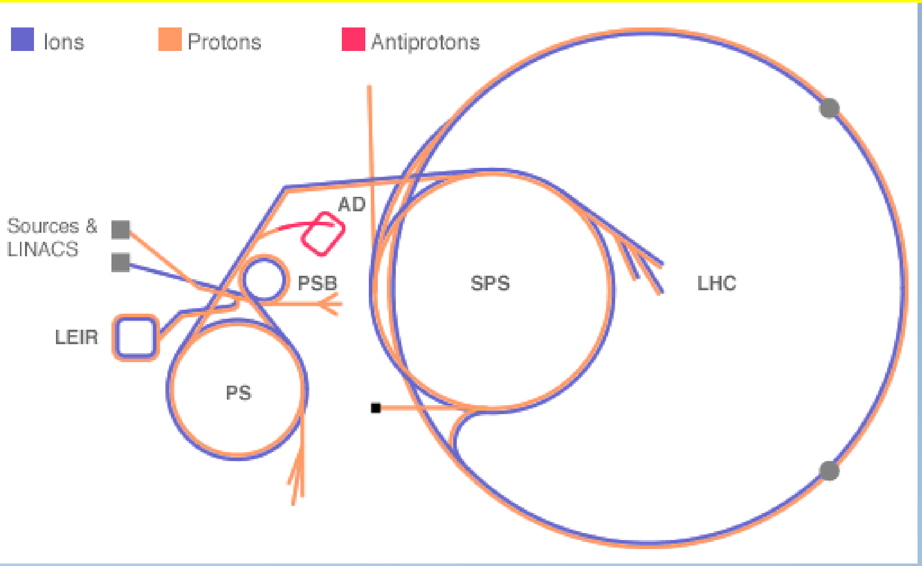
$$E_{CME} = 2E$$

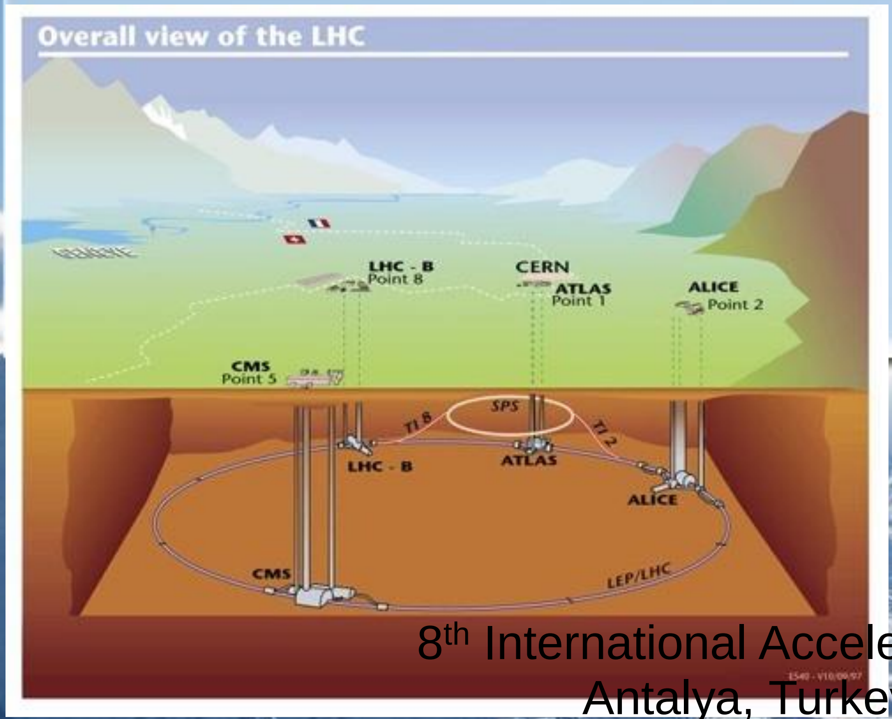
Evolution of Proton/Antiproton Colliders



LHC

- Latest step to higher enegie
- Reuse of LEP tunnel
  - Circumference 27km
- 14TeV proton-proton
  - magnetic field 8.33 Tesla



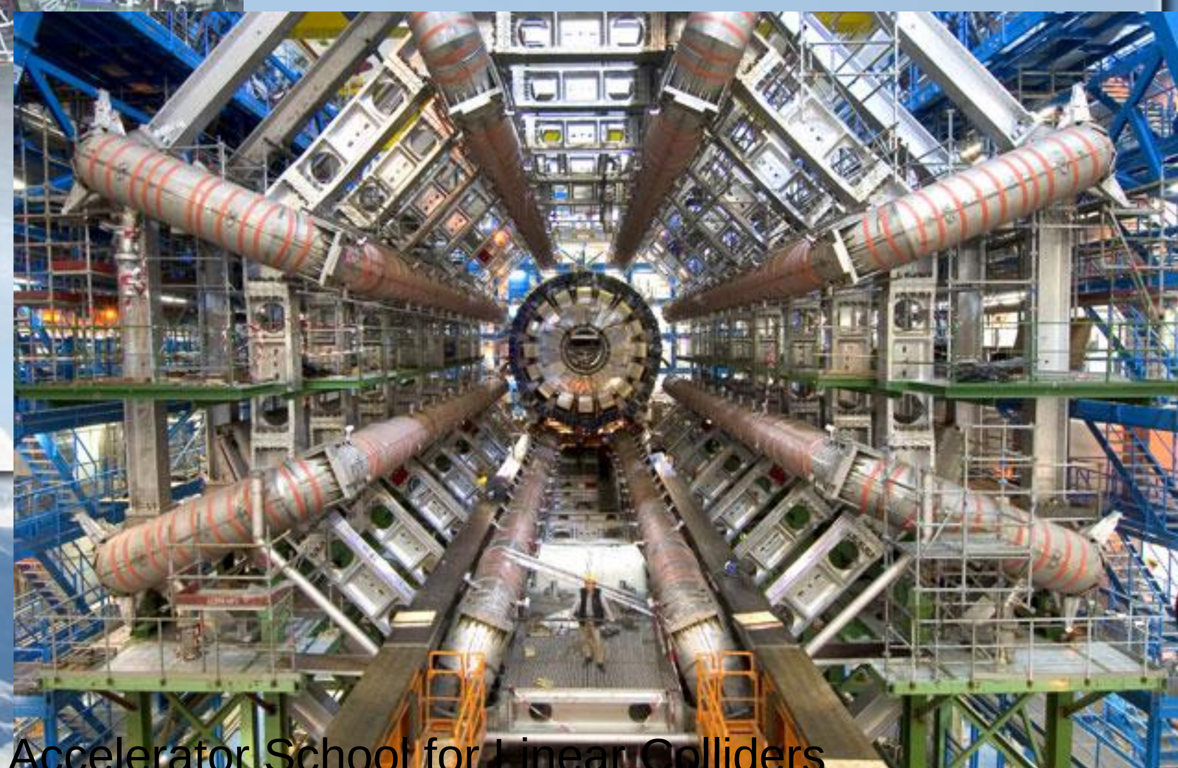


http://athome.web.cern.ch/athome/LHC/lhc.html


LHC

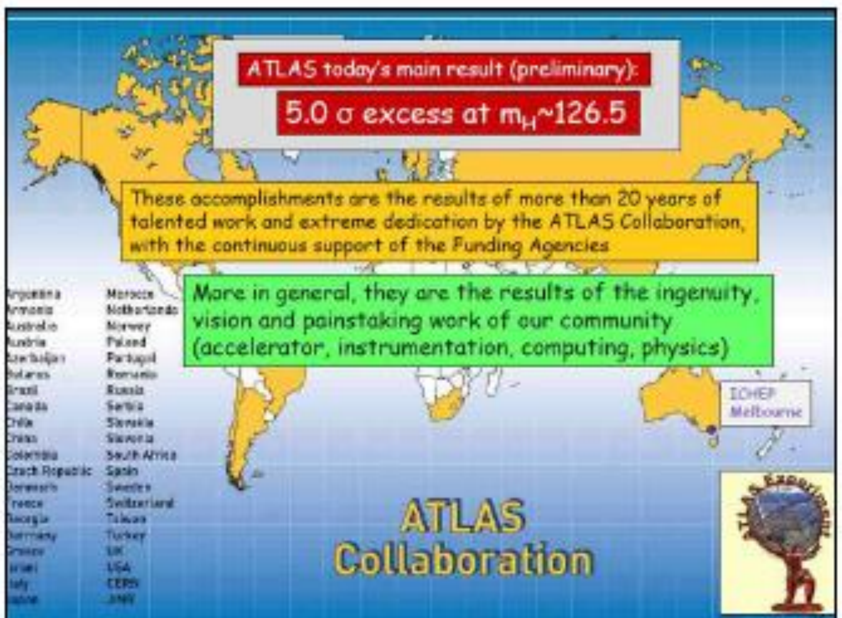
Technology of Superconducting Magnet was essential

Atlas Detector



July 4, 2012


In summary
We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !

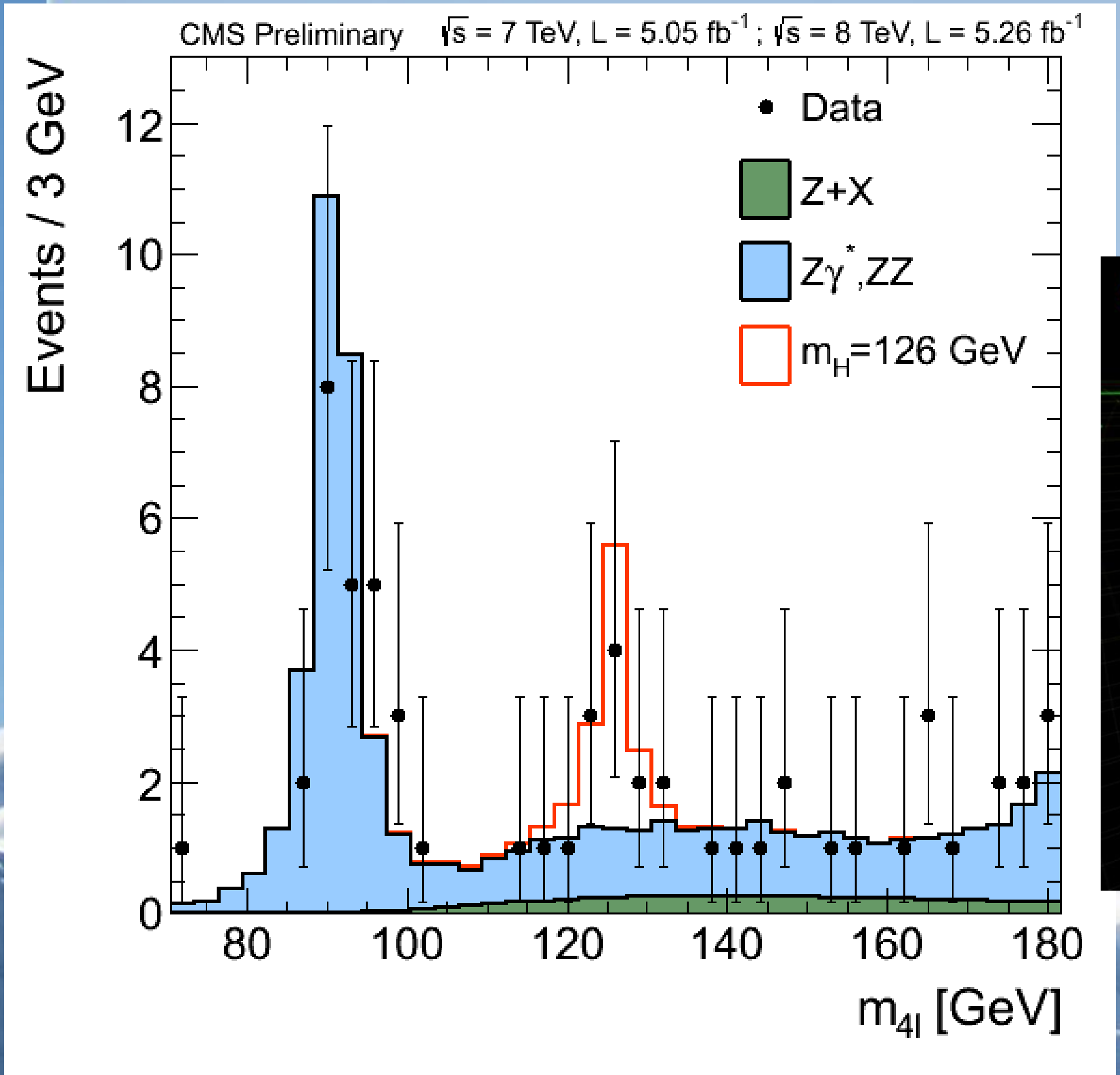

ATLAS today's main result (preliminary):
5.0 σ excess at m_H~126.5
These accomplishments are the results of more than 20 years of talented work and extreme dedication by the ATLAS Collaboration, with the continuous support of the Funding Agencies
More in general, they are the results of the ingenuity, vision and painstaking work of our community (accelerator, instrumentation, computing, physics)
ICHEP Melbourne
ATLAS Collaboration

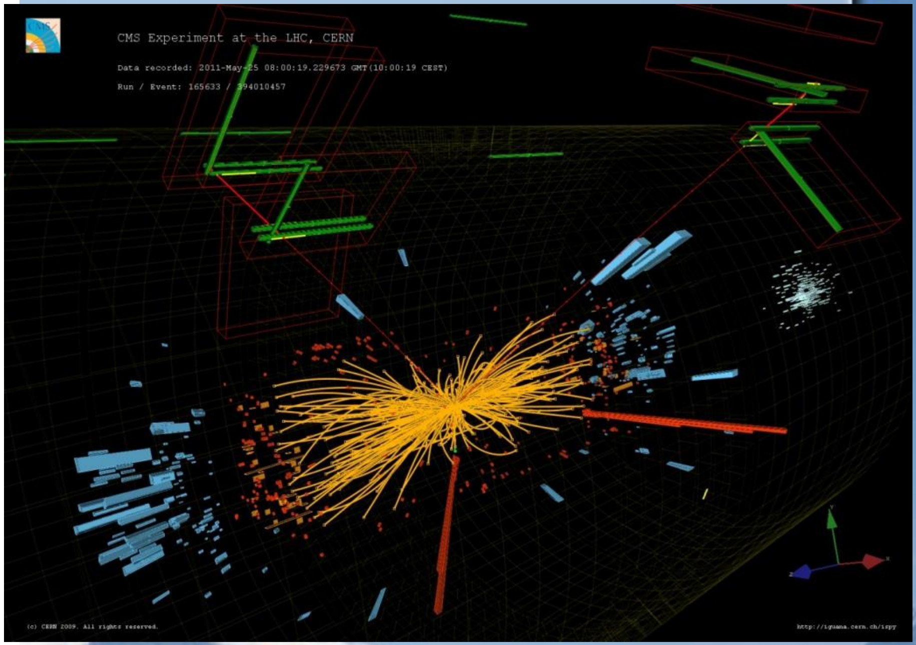

CERN
Higgs search
update 04.07.2012


Higgs searc
update 04.07


Higgsdependence Day
July 4, 2012
Independence from the mass-less Lagrangian!
H. Murayama

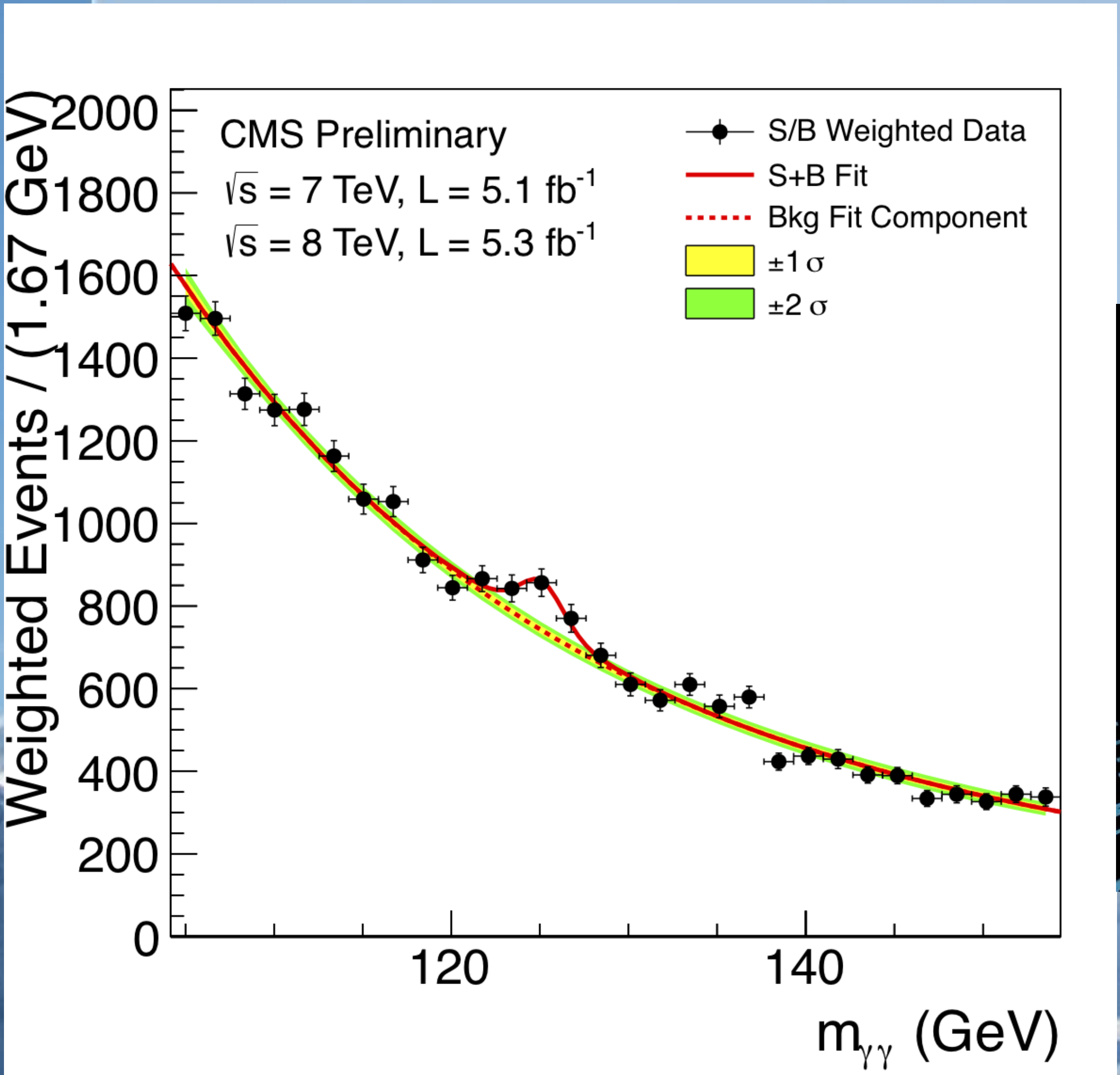
Higgs Discovery
4 lepton channel

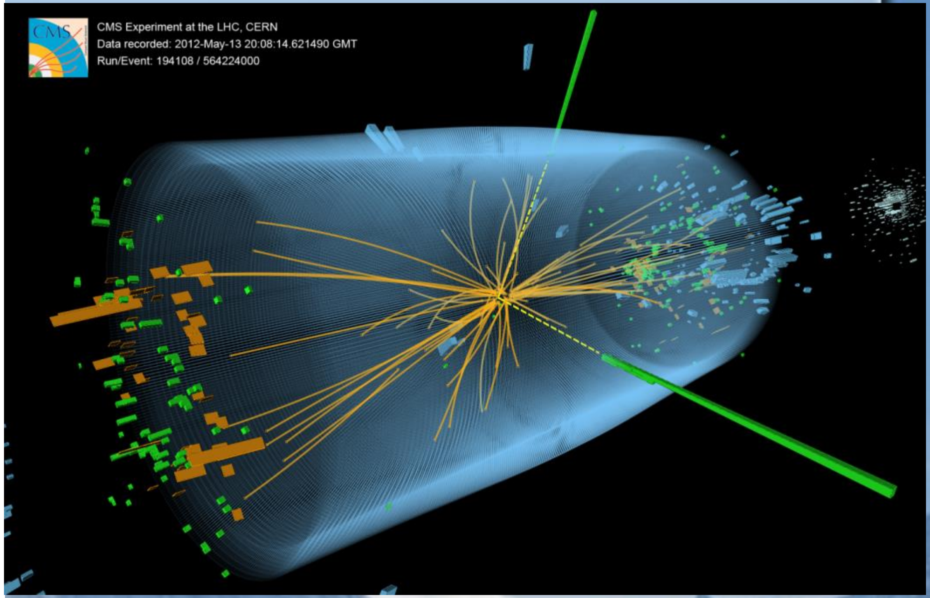




Higgs Discovery

2γ channel





LHC is marvelous!

But …

LHC discovered Higgs. SUSY and other particle can be observed eventually.

Technically, PS is possible to go higher energy.

Hadron collider is only thing which we have to do?

I will try to explain that we need another booster to go forward.

Hadron Collider

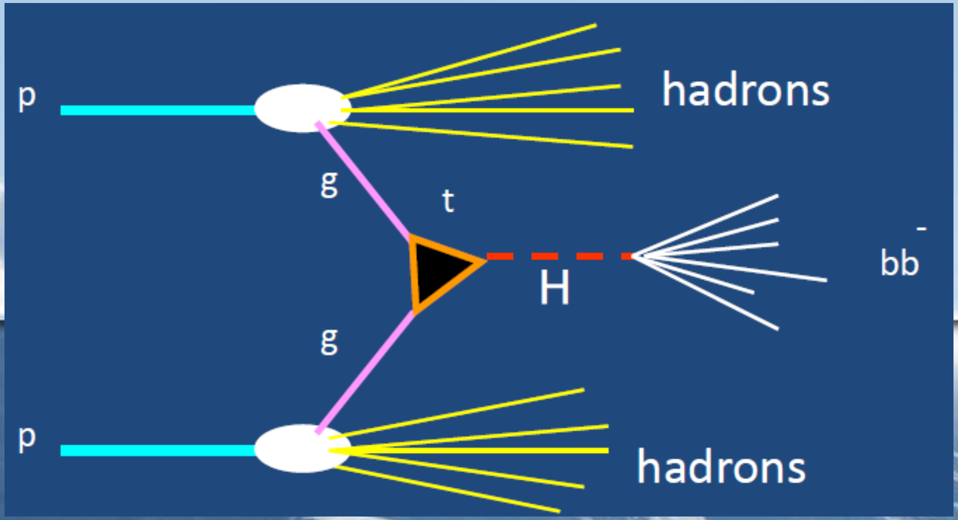
Hadron (proton/antiproton) is easier to accelerate to high energies owing to the absence of synchrotron radiation

Already 14TeV will be reached in a few years (LHC)

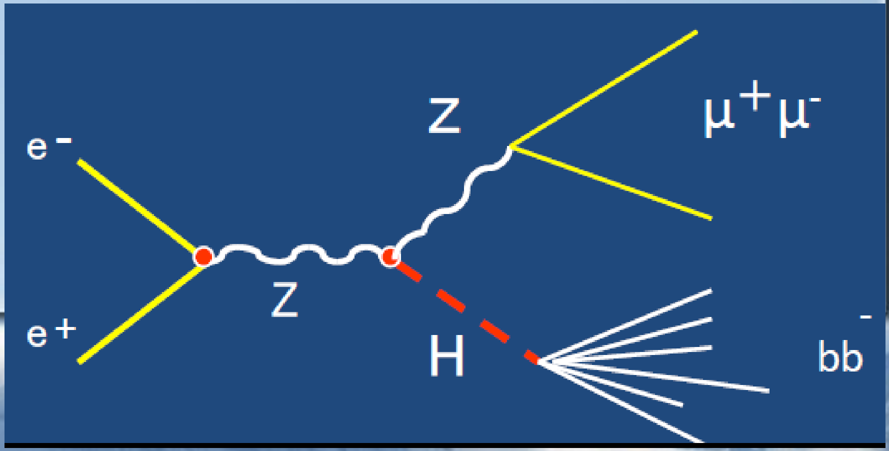
Events are complicated because proton is not an elementary particle

Proton : uud + sea quark + gluon.

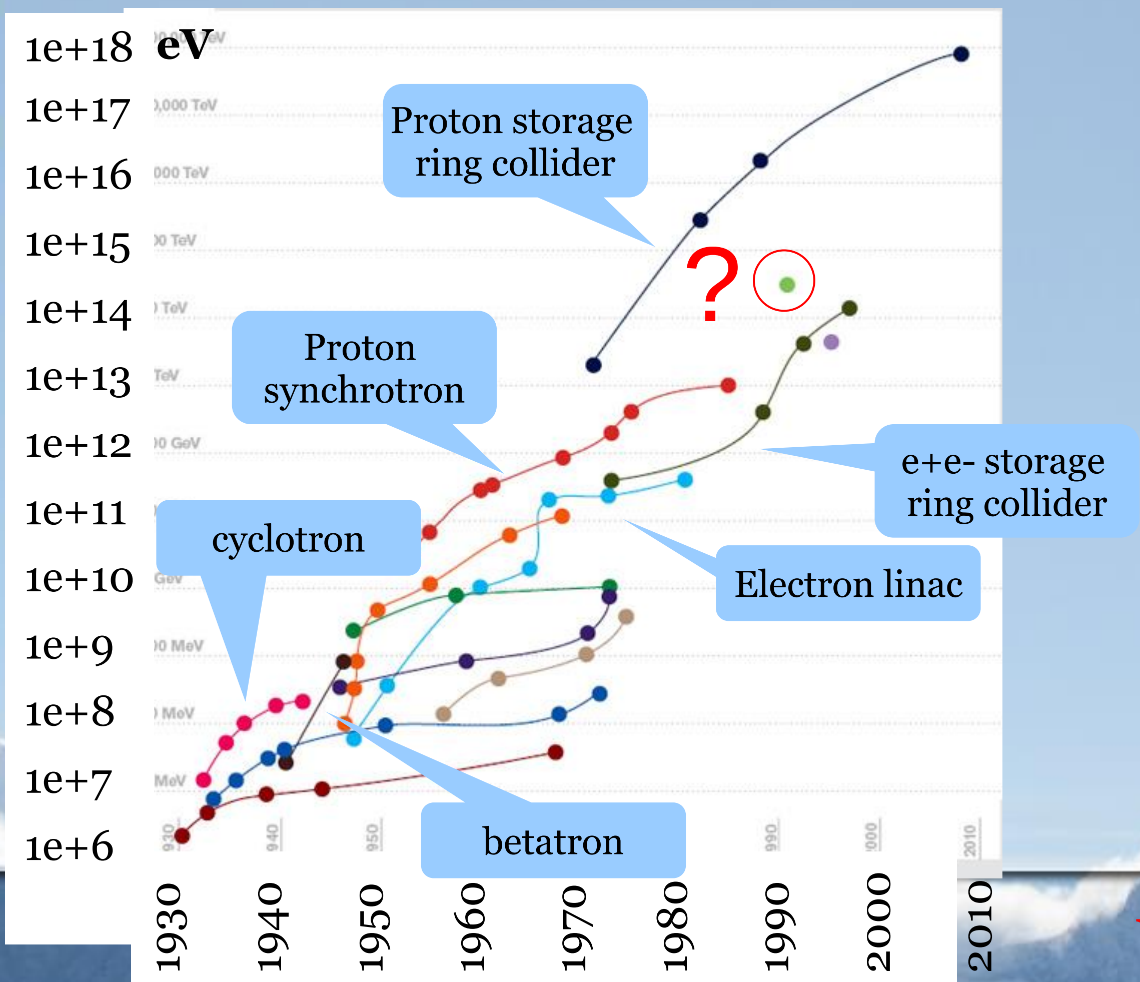
Higgs production in pp



Higgs production in e+e-



Livingston Plot :
Moore's law in accelerator



We need another Booster!

From Symmetry Magazine

Summary

- Curiosity is our driving force for physics research.
- Universe is still mysterious for us. We want understand it.
- SM of particle physics has been established. The last member, Higgs particle was discovered in 2012.
- In the evolution, accelerator was another.
- We need keep our progress. That requires continuous evolutions on the accelerator technology and science.