

# Introduction to Particle Physics

Prof. Lucio Cerrito  
*Università e INFN Roma Tor Vergata*

06/03/2026

ATLAS Detector Under construction  
October 2005

What is the subatomic  
structure of our Universe ?

What are we really made of ?

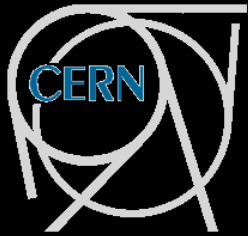
What are the fundamental forces ?

Can we even answer these questions ?

... and how ?

July 4<sup>th</sup>, 2012

# European Organization for Nuclear Research

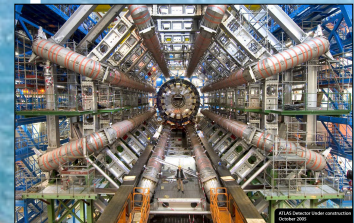


Franco-Swiss border, near Geneva

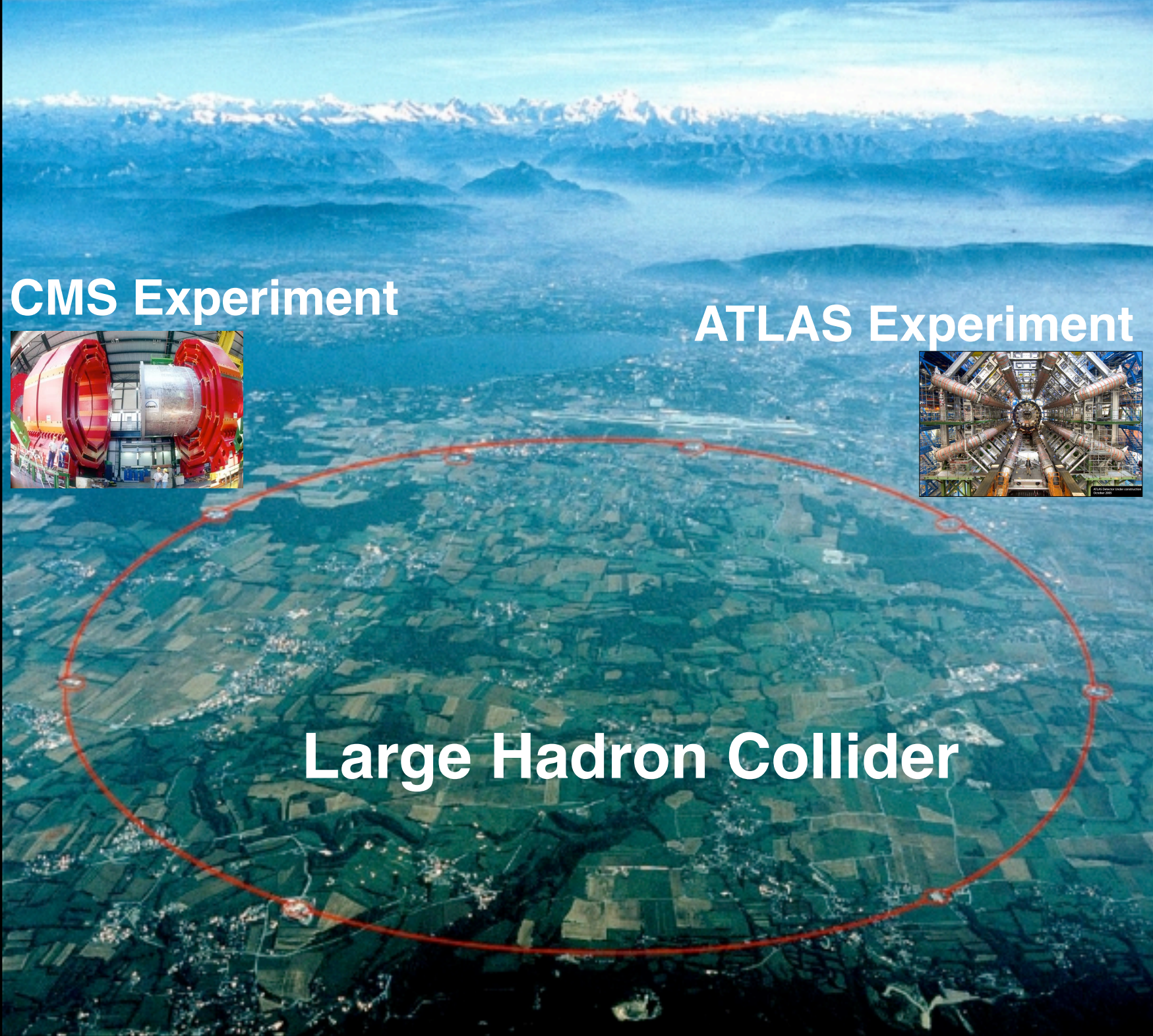
**CMS Experiment**

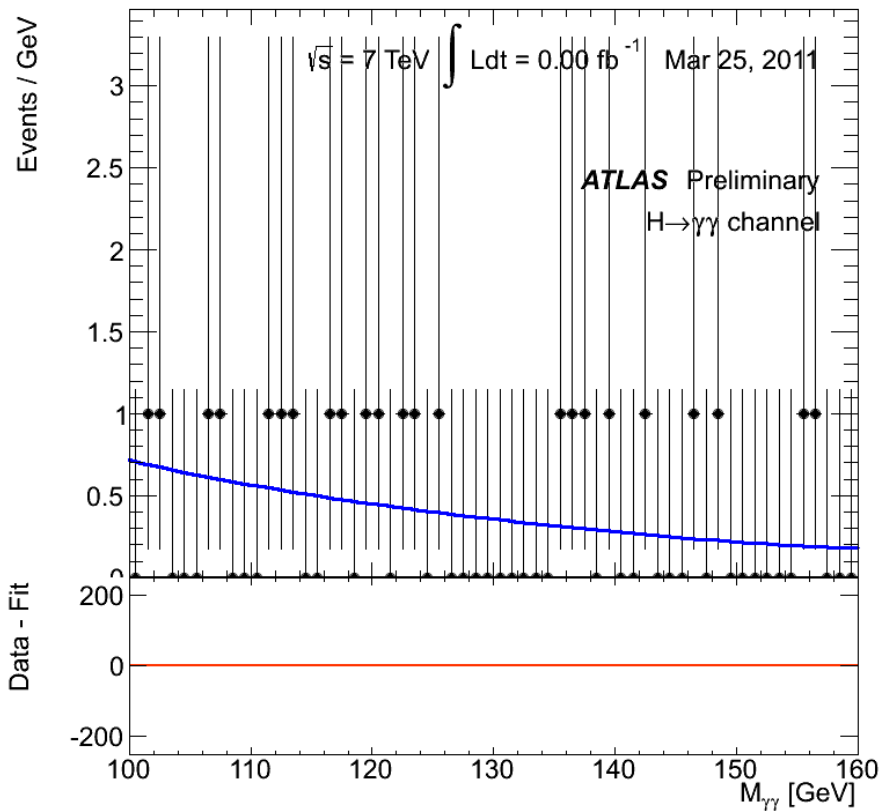


**ATLAS Experiment**

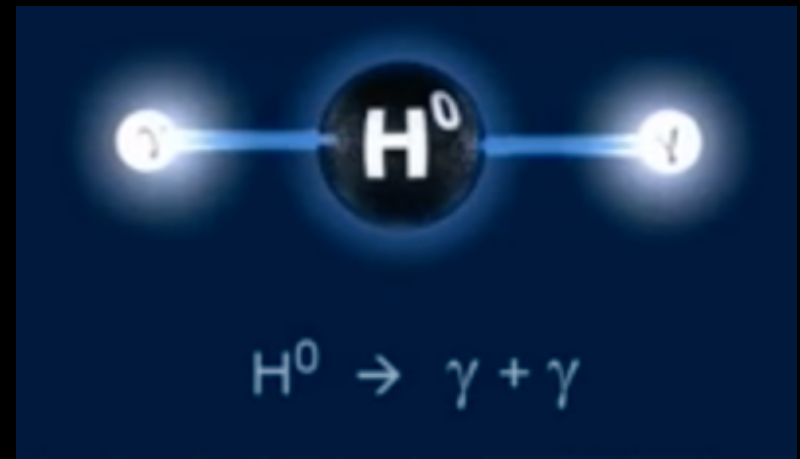


**Large Hadron Collider**





# Discovery of the Higgs Boson



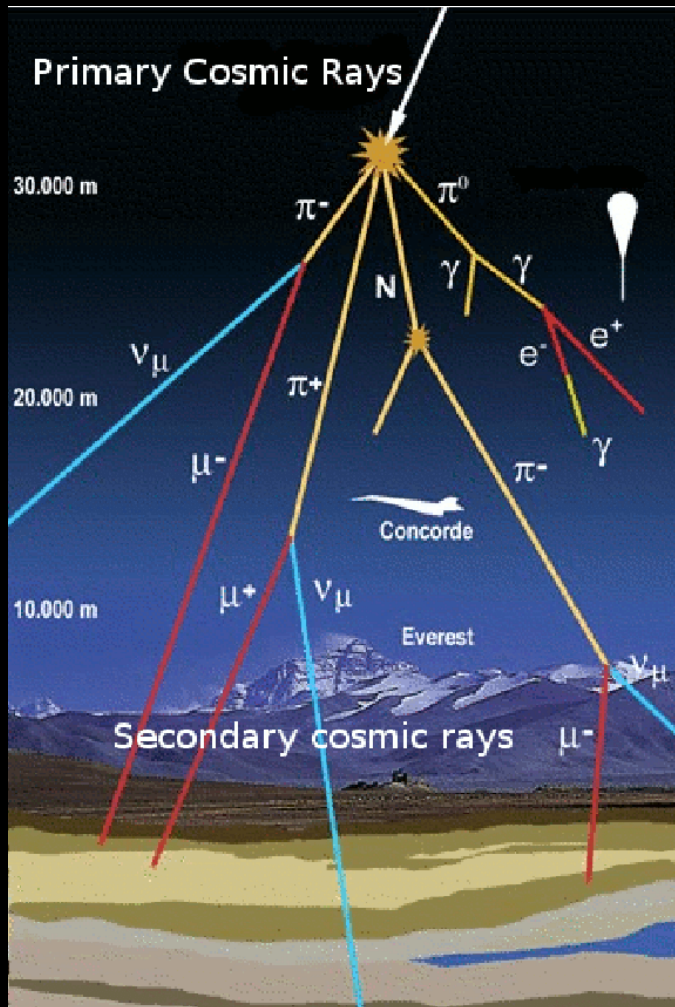
Existence of a Higgs field showing ripples

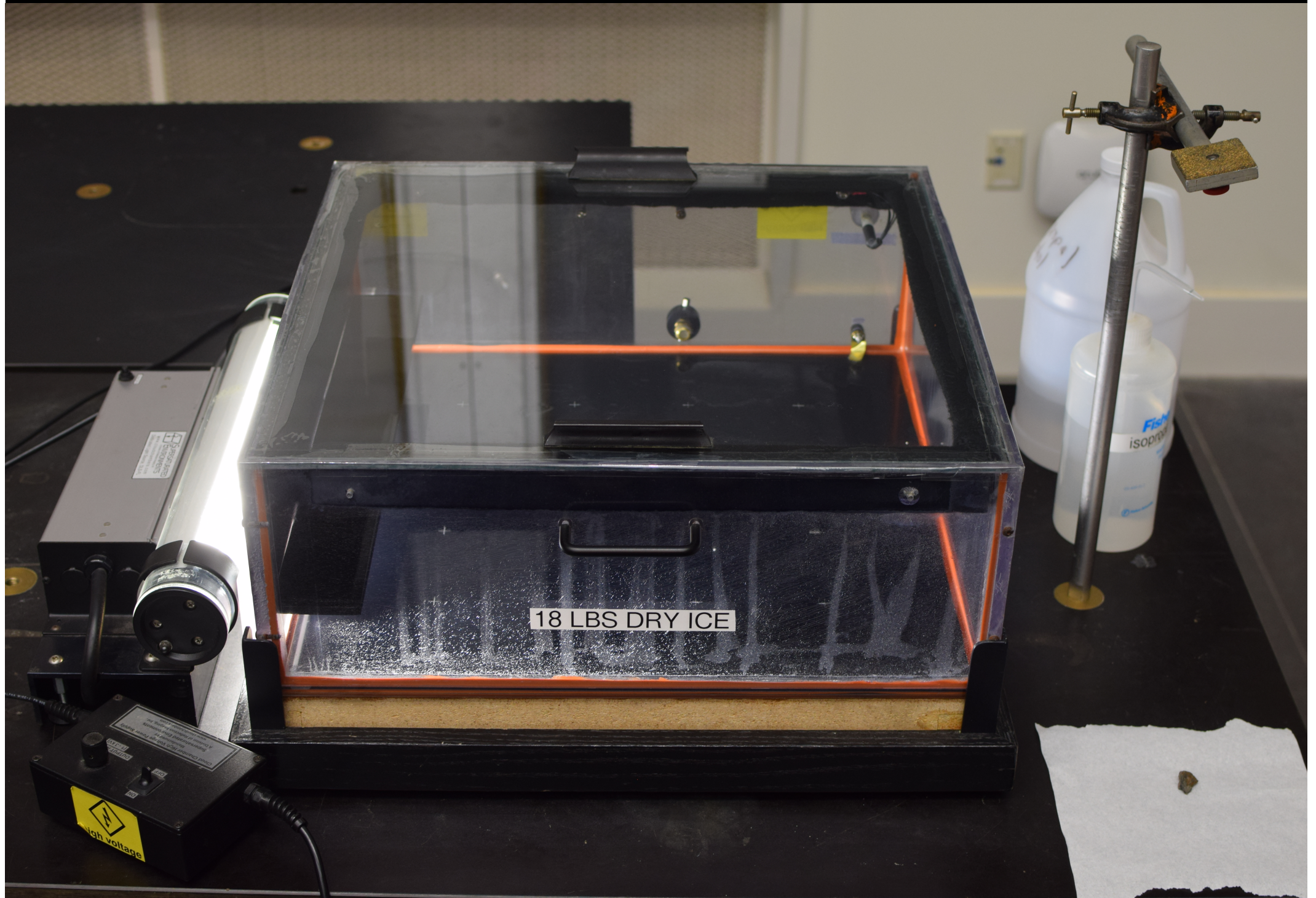


Nobel Prize in  
Physics, 2013

# **PART 1**

## The Subatomic World





18 LBS DRY ICE

Fish isopropanol

high voltage

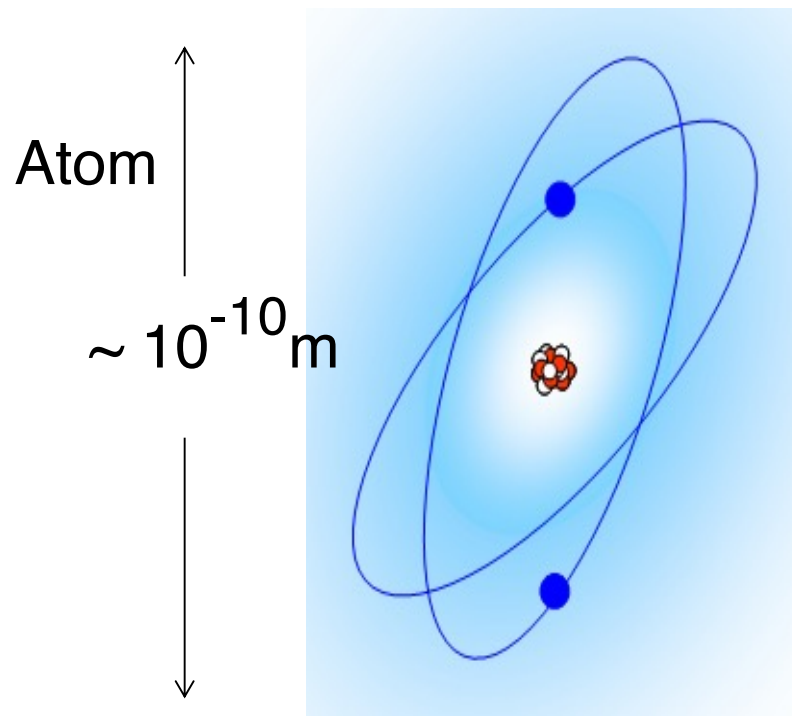




# Structure of the Atom

1930s

Simple picture  
3 elementary  
particles



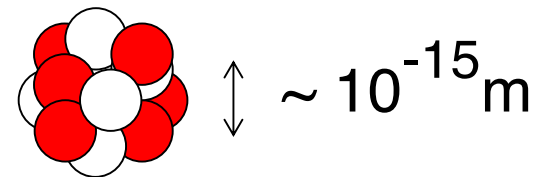
Electron already discovered  
in 1897 by J. J. Thomson



1911 nucleus, electron

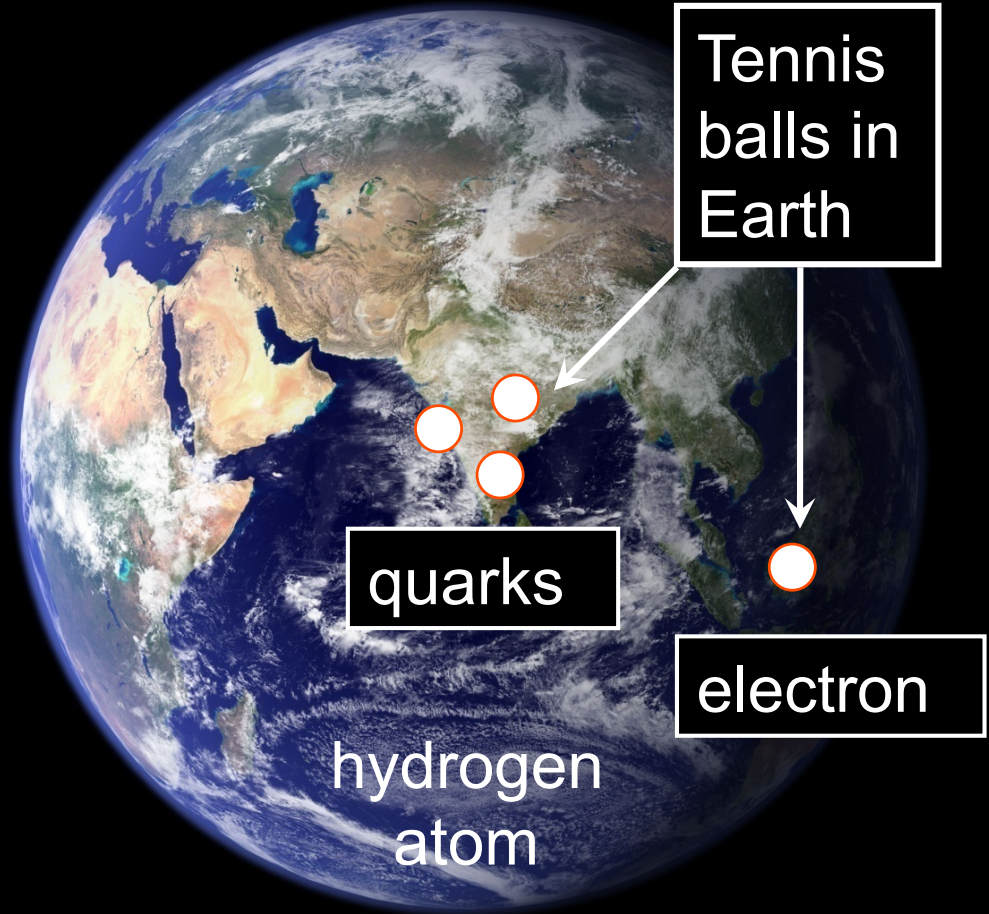
electromagnetism  
long range  $1 / r^2$

1932 neutron discovered  
by James Chadwick

Nucleus



Proton +  }  
Neutron  } strong force  
short range

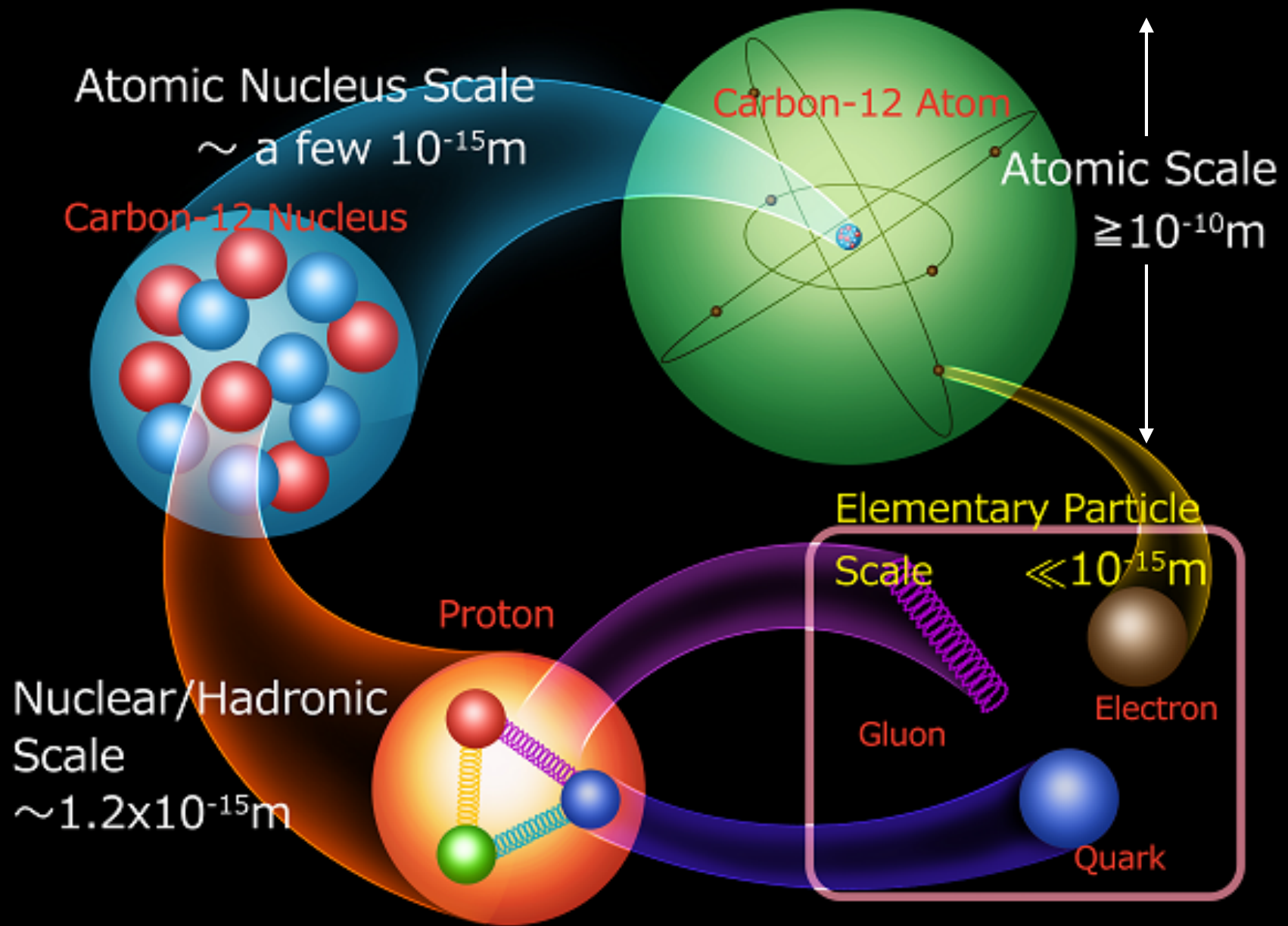


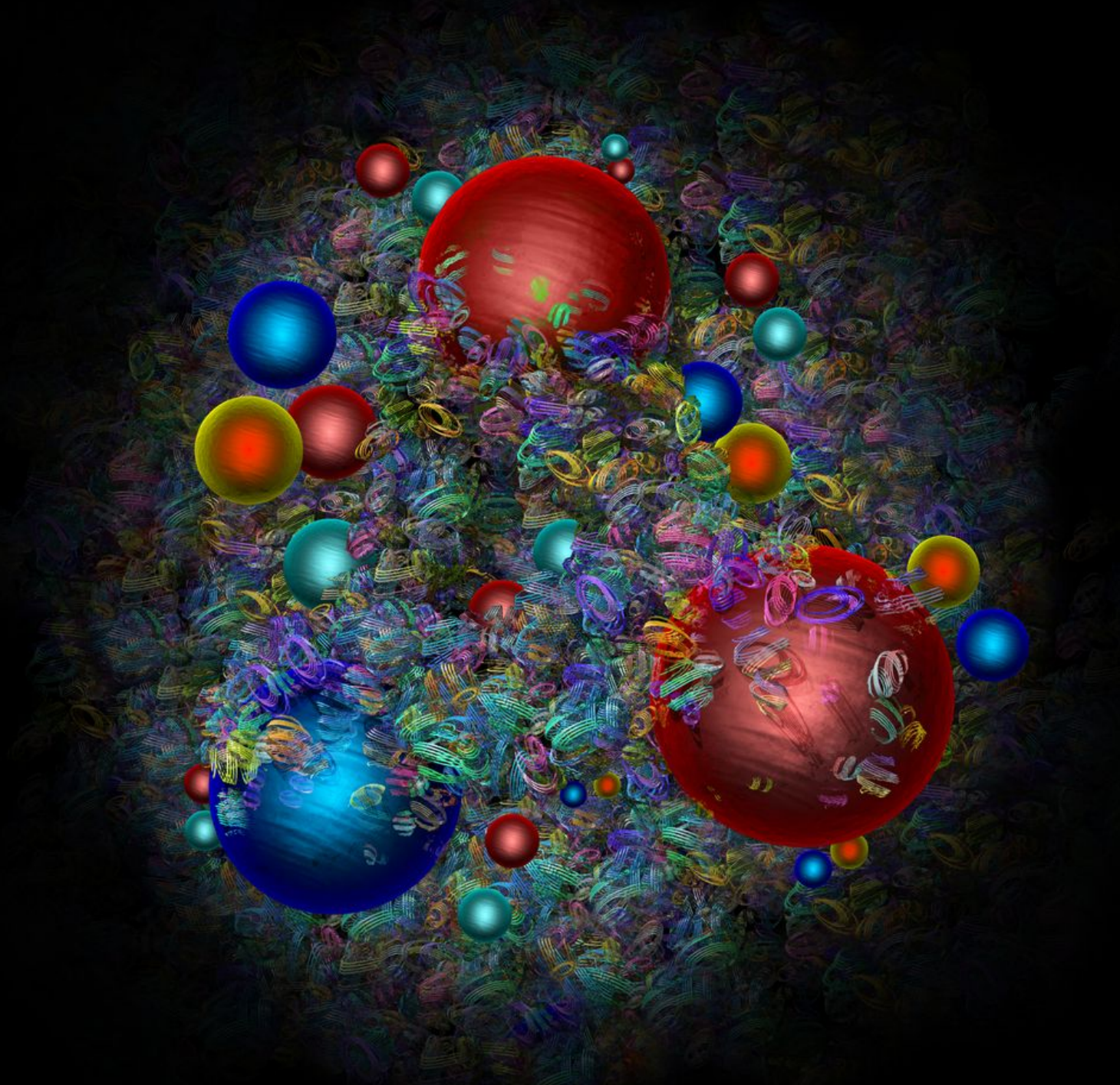
Tennis balls in Earth

quarks

electron

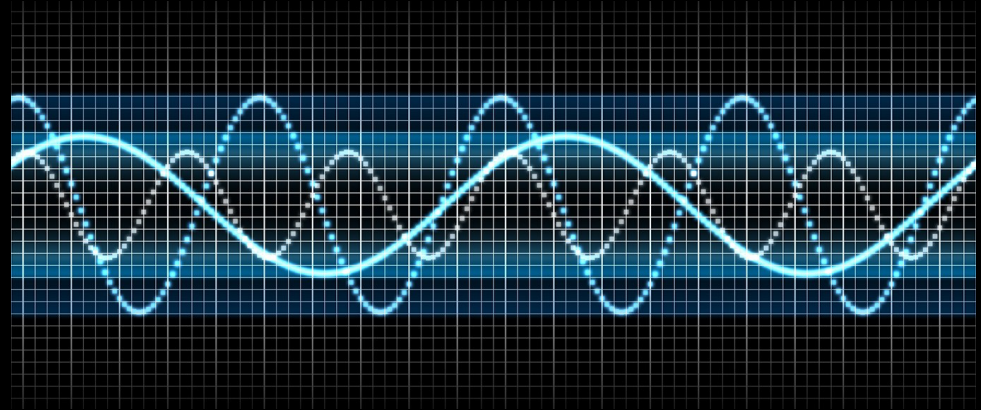
hydrogen atom



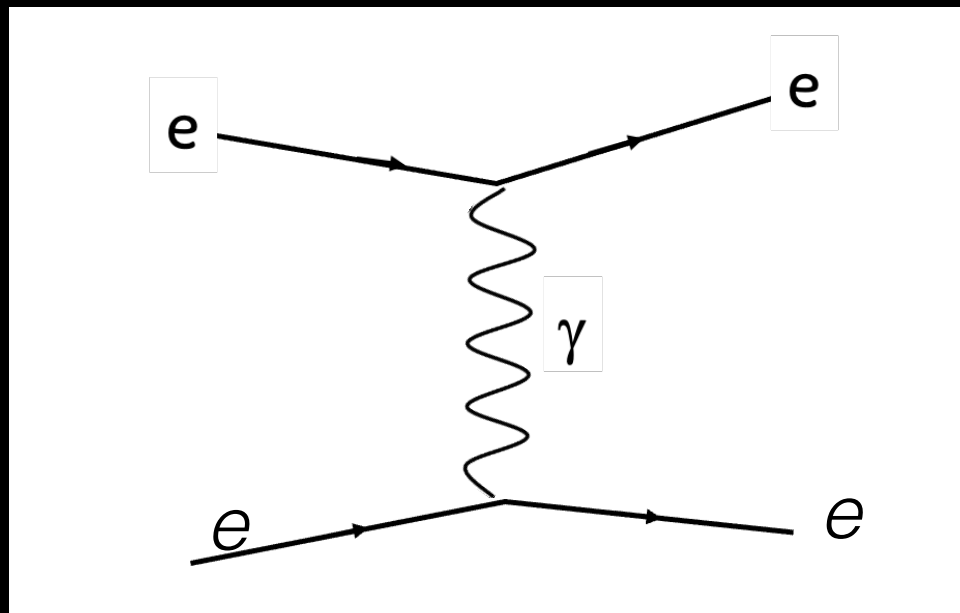
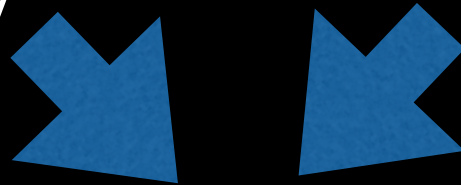




Special Relativity



Quantum Mechanics



Feynman  
Diagram of a  
collision

# Constituents

How can we find internal structure?

Insect



1 lens : Magnifying glass

2 lenses : Microscope

3 lenses : No improvement

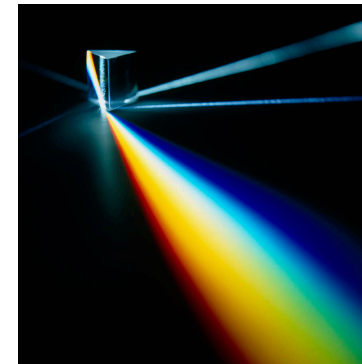
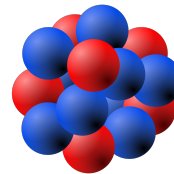


Resolution limited by wavelength of light =  $\lambda$

Visible light wavelength  $\lambda \sim 5 \times 10^{-7}$  m

This is 5,000 times size of atom

500 million times size of nucleus



To “probe” elementary particles need wavelengths  $\lambda$   
lower by factor more than a billion !

## Quantum physics to the rescue

Particles have  
wave properties

wavelength  $\lambda = \frac{h}{p}$

Planck constant  $h$   
momentum  $p$

“See” small objects

- small wavelength
- high momentum
- high energy
- large accelerator

To observe the smallest objects  
we need the largest machines !

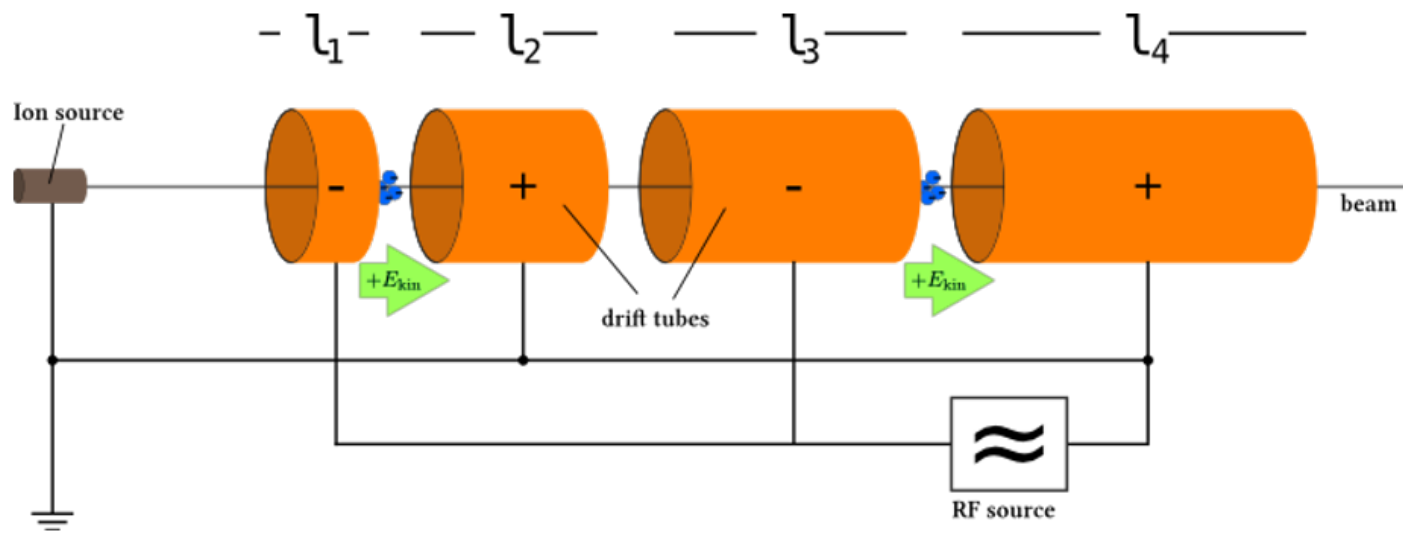
Non-relativistic

$$p = m v$$

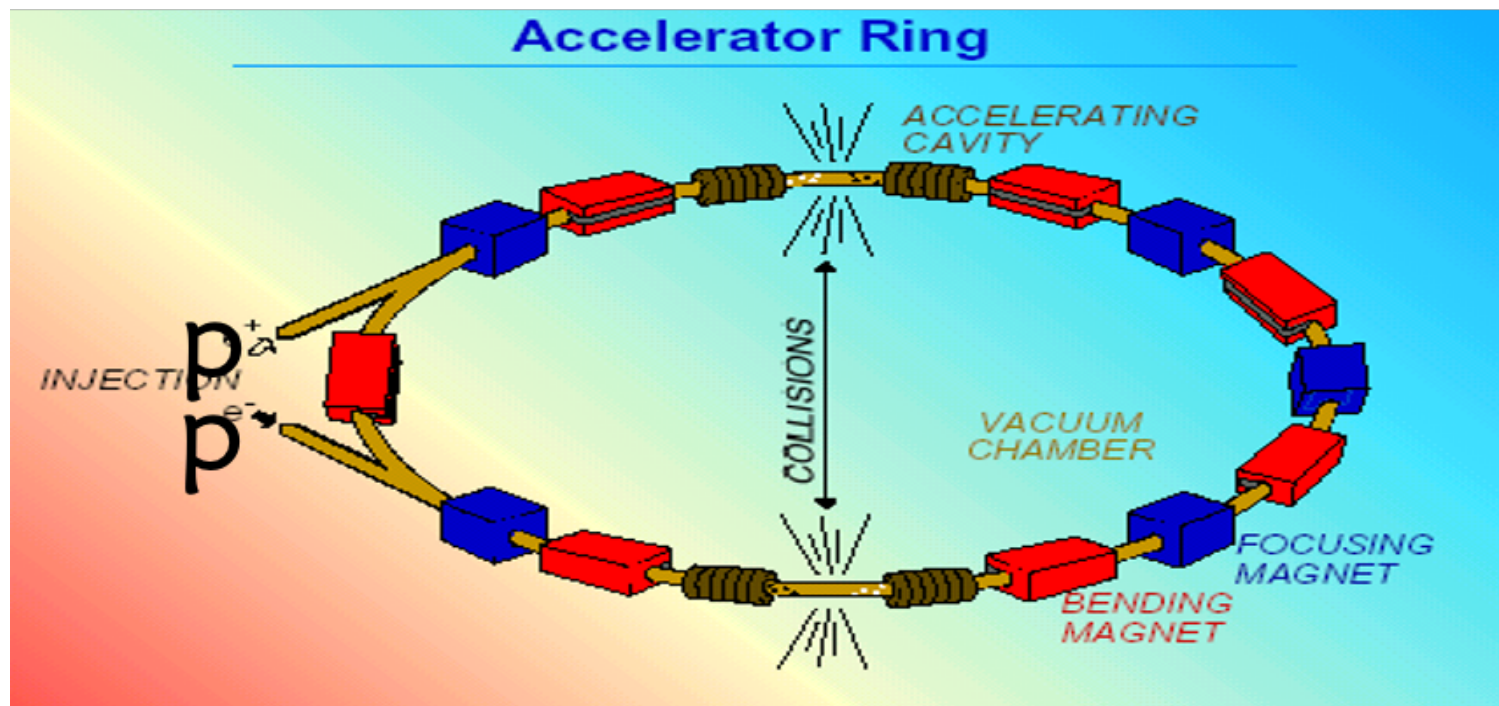
mass x velocity

Relativistic

$$p = \gamma m v$$
$$\gamma = 1 / (1 - v^2/c^2)^{1/2}$$



Linear



Circular

# Neutrinos



W. Pauli



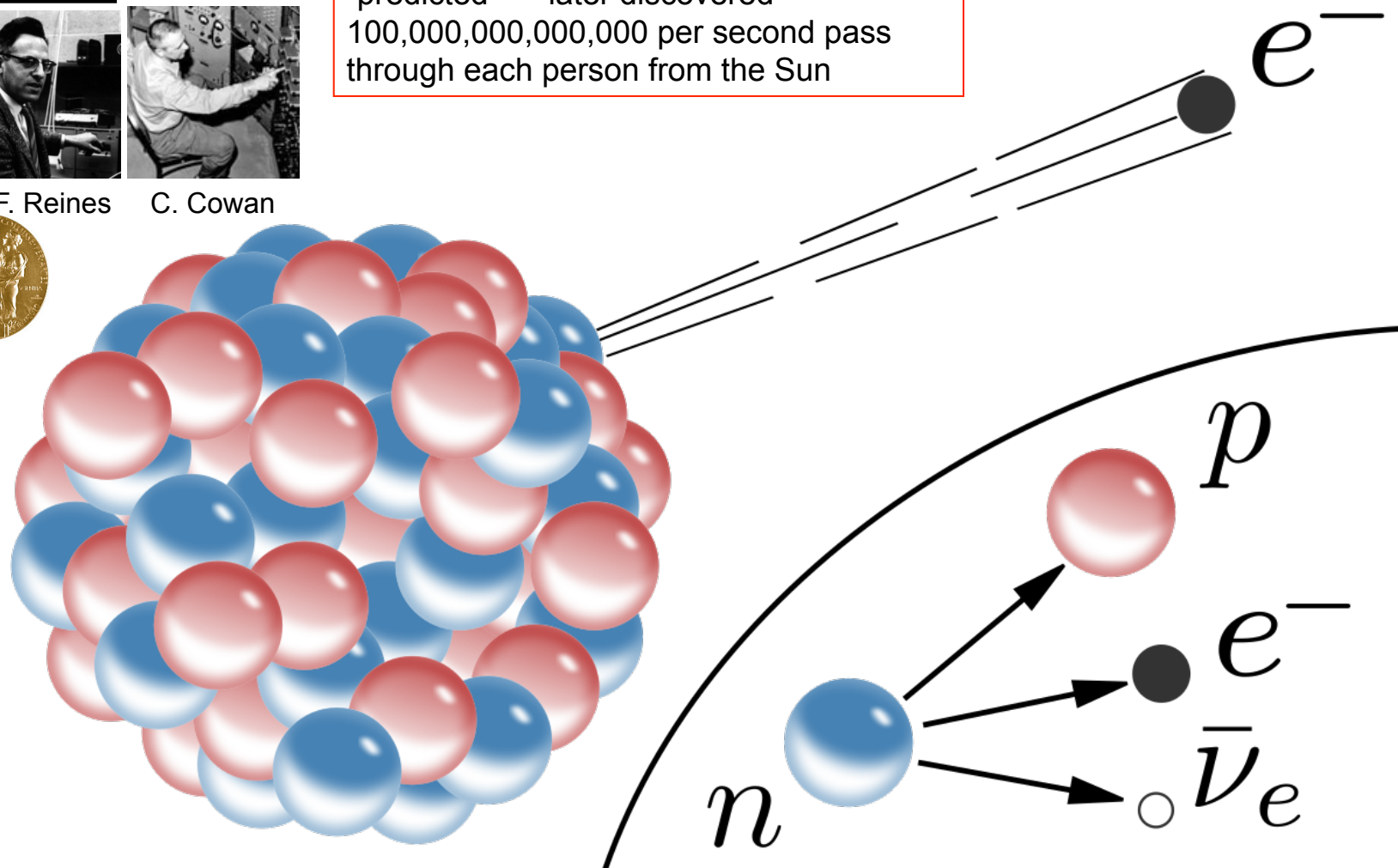
F. Reines



C. Cowan



Feel weak force  
"predicted" → later discovered  
100,000,000,000,000 per second pass  
through each person from the Sun



Leptons

electron  
 $e^-$  -1

neutrino  
 $\nu_e$  0

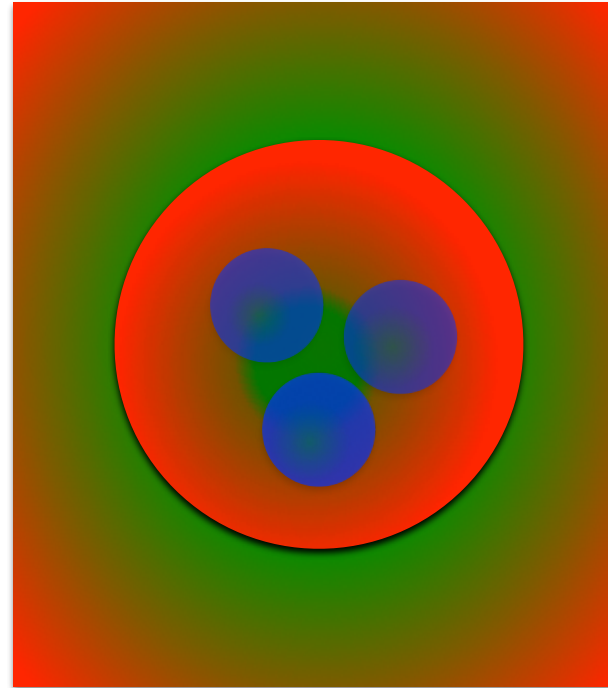
do not  
feel  
strong  
force

Quarks

up  
u +2/3

down  
d -1/3

feel  
strong  
force



Proton u u d  
 $+2/3 +2/3 -1/3 = +1$   
Neutron u d d  
 $-1/3 -1/3 +2/3 = 0$

Leptons	electron $e^-$ -1	muon $\mu^-$ -1	tau $\tau^-$ -1
	neutrino $\nu_e$ 0	neutrino $\nu_\mu$ 0	neutrino $\nu_\tau$ 0
Quarks	up u +2/3	charm c +2/3	top t +2/3
	down d -1/3	strange s -1/3	bottom b -1/3

x 2 for antiparticles

3 generations

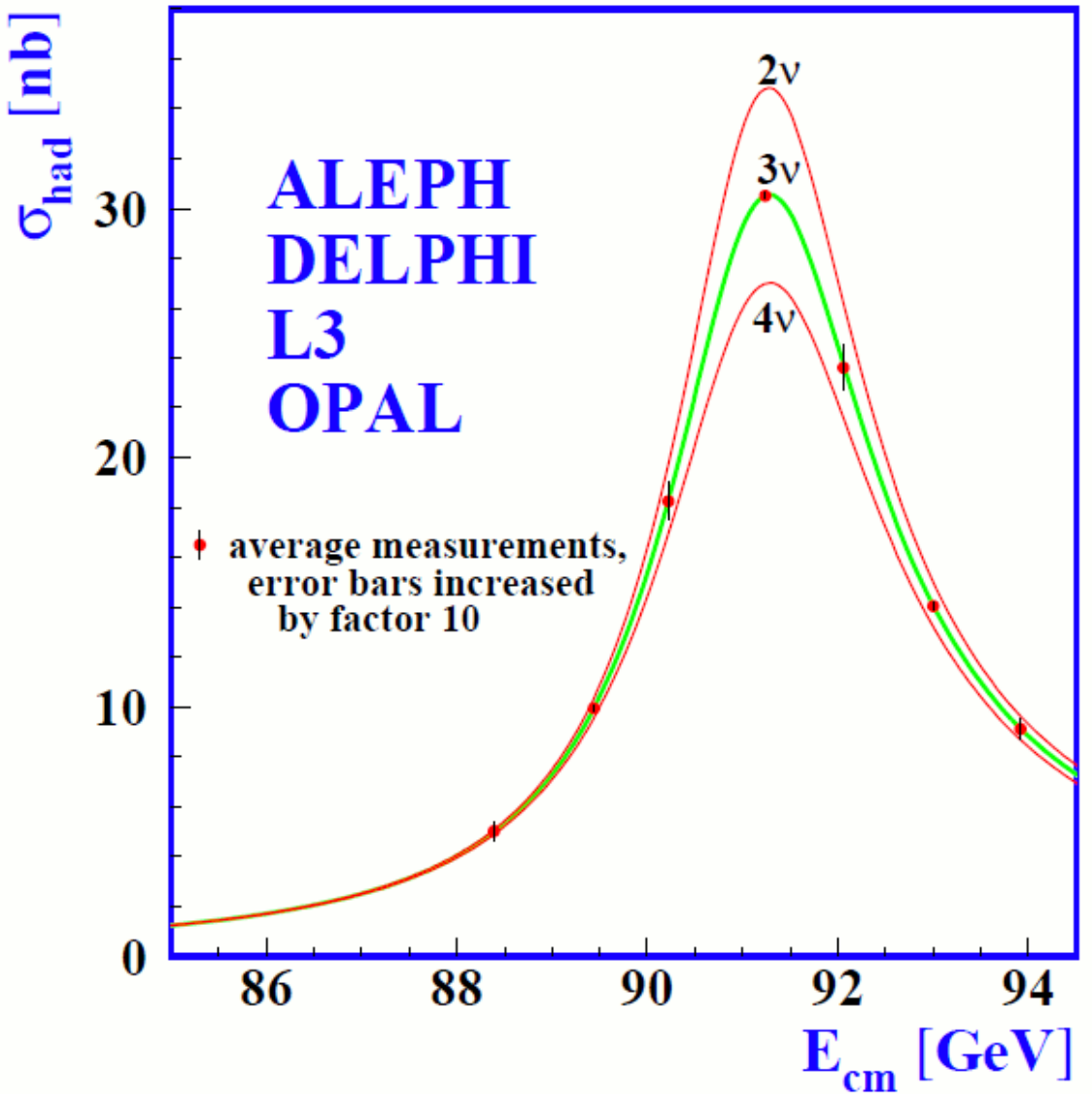
At high energies  
can produce two  
more generations  
of quarks and  
leptons

# Discovery of top quark Pattern completed March 2<sup>nd</sup>, 1995



U.S. Fermi  
National Accelerator  
Laboratory

Illinois - Chicago



## Uncertainty Principle

$$\Delta E \Delta t \sim h/2\pi$$

Z line shape

$$N_{\nu} = 2.994 \pm 0.011$$

Leptons	electron $e^-$ -1	muon $\mu^-$ -1	tau $\tau^-$ -1
	neutrino $\nu_e$ 0	neutrino $\nu_\mu$ 0	neutrino $\nu_\tau$ 0
Quarks	up u +2/3	charm c +2/3	top t +2/3
	down d -1/3	strange s -1/3	bottom b -1/3

MATTER

Leptons	electron $e^-$ -1	muon $\mu^-$ -1	tau $\tau^-$ -1
	neutrino $\nu_e$ 0	neutrino $\nu_\mu$ 0	neutrino $\nu_\tau$ 0
Quarks	up u +2/3	charm c +2/3	top t +2/3
	down d -1/3	strange s -1/3	bottom b -1/3

ANTI-MATTER

### Antiparticles



P. Dirac

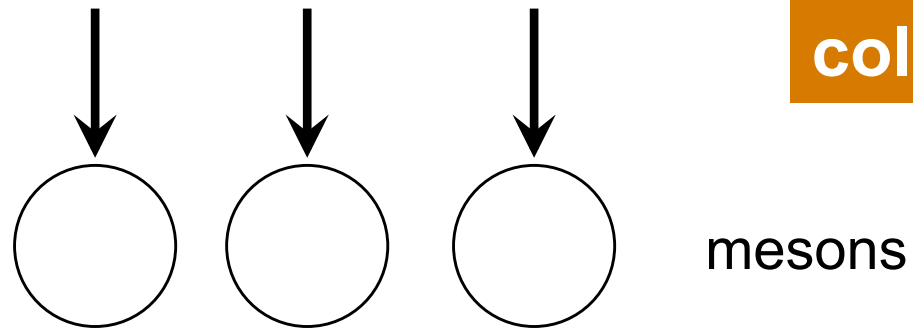
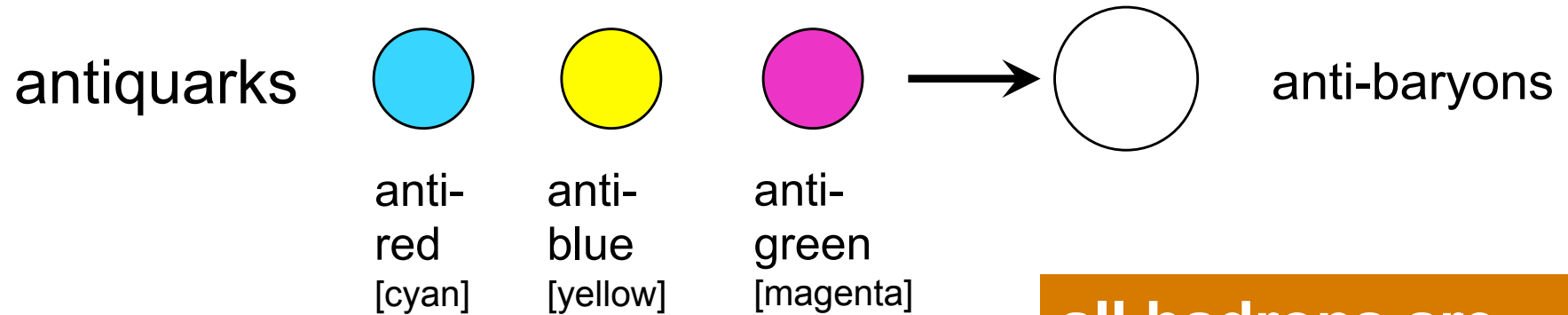
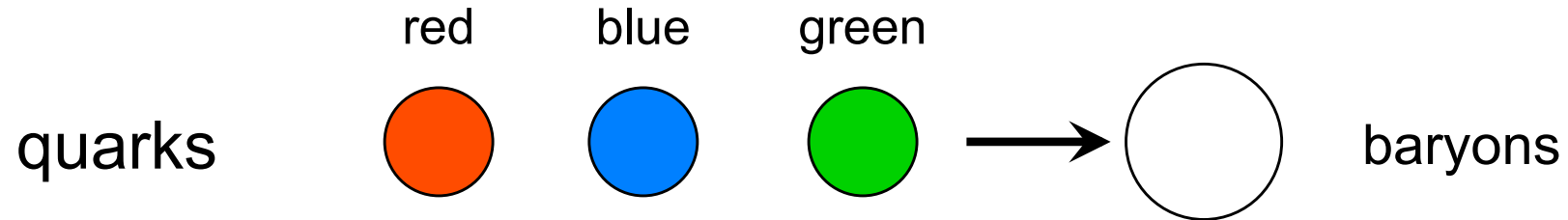


C. Anderson



Equal and opposite properties  
 "predicted" → later discovered  
 Annihilate with normal particles  
 Now used in PET scans

# Colour: Strong force “equivalent” of charge



**all hadrons are colourless (white)**

Gravity  
Strength:  $6 \times 10^{-39}$   
Range: Infinite  
Exchange: Graviton?



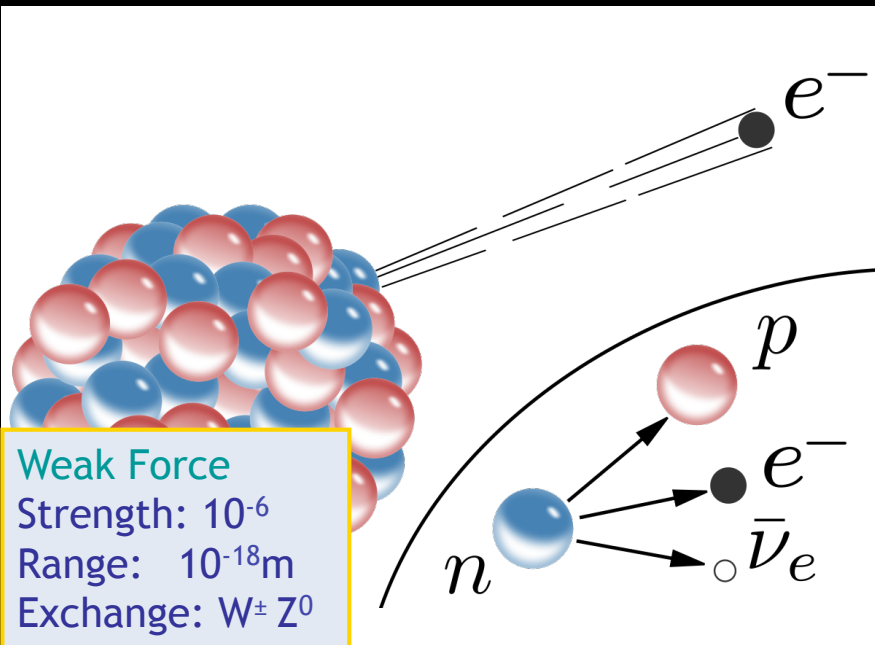
Gravitational Force

Model of a helium atom

Electromagnetic Force  
Strength:  $1/137$   
Range: Infinite  
Exchange: Photon

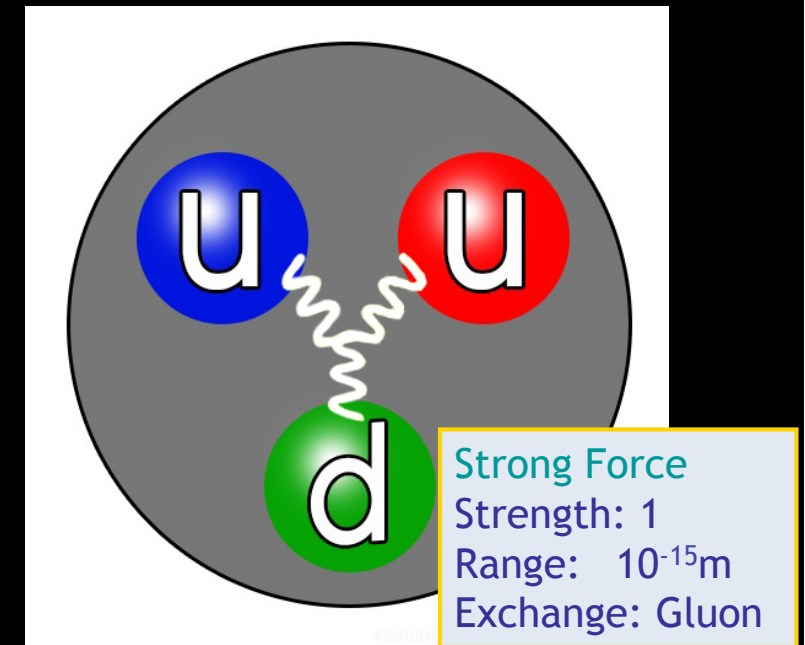


Electromagnetic Force



Weak Force  
Strength:  $10^{-6}$   
Range:  $10^{-18}m$   
Exchange:  $W^{\pm} Z^0$

Weak Nuclear Force



Strong Force  
Strength: 1  
Range:  $10^{-15}m$   
Exchange: Gluon

Strong Nuclear Force



Falling



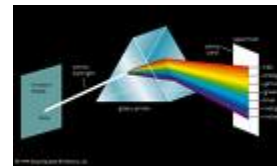
Planetary Motion



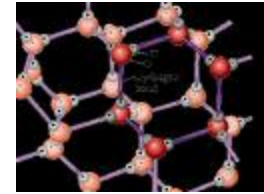
Magnetism



Electricity



Light



Molecular Forces

Gravity

Electromagnetism

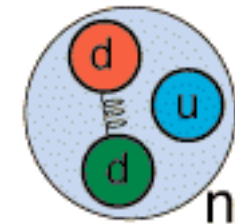
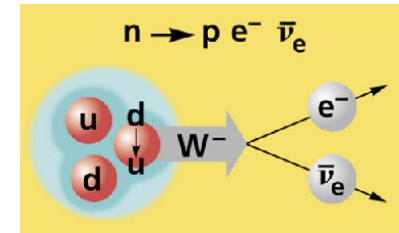
Weak Force

Electroweak Force

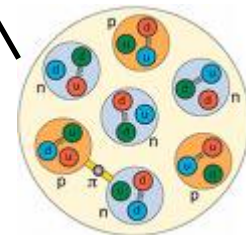
Strong Force

Grand Unification?

Theories of Everything?



Nuclear Forces



## **PART 2**

A Particle Unlike Any Other

# The Standard Model

$$E = \sqrt{(\vec{p}c)^2 + (m_0c^2)^2}$$

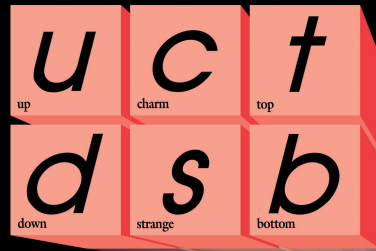
$$\vec{p} = 0 \Rightarrow E = m_0c^2$$

$$\begin{aligned} \mathcal{L}_{\text{StandardModel}} = & -\frac{1}{2}\partial_\mu g_\nu^\alpha \partial_\mu g_\nu^\alpha - g_s f^{abc} \partial_\mu g_\nu^a \partial_\mu g_\nu^b g_\nu^c - \frac{1}{2} g_s^2 f^{abc} f^{abd} g_\nu^c g_\nu^d g_\nu^e + \\ & \frac{1}{2} ig^2 (\bar{\psi} \gamma^\mu \psi) g_\mu^a + G^a \partial^\mu G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\mu W_\nu^+ \partial_\mu W_\nu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\mu Z_\nu^0 \partial_\mu Z_\nu^0 - \frac{1}{2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\ & \frac{1}{2} m_H^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2} M^2 \phi^0 \phi^0 - \beta_\lambda \frac{1}{2} \lambda \phi^4 + \\ & \frac{3\lambda}{8} H^4 + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) + \frac{3M^2}{8} \alpha_h - ig_{c_w} [\partial_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - Z_\nu^0 (W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+) + Z_\nu^0 (W_\mu^+ \partial_\mu W_\nu^- - \\ & W_\mu^- \partial_\mu W_\nu^+)] - ig_{s_w} [\partial_\mu A_\nu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\mu W_\nu^- - \\ & W_\mu^- \partial_\mu W_\nu^+) + A_\nu (W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\ & \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\mu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\ & g^2 s_w^2 (A_\mu W_\nu^+ A_\mu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\mu^- W_\nu^+) - 2A_\mu Z_\nu^0 W_\mu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\ & \frac{1}{2} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\ & g M W_\mu^+ W_\nu^- H - \frac{1}{2} g \frac{M^2}{2} Z_\mu^0 Z_\nu^0 H - \frac{1}{2} ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\ & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} ig [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\ & \phi^+ \partial_\mu H)] + \frac{1}{2} ig \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{M^2}{2} Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\ & ig_{s_w} M A_\nu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\ & ig_{s_w} A_\nu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{2} g^2 W_\mu^+ W_\nu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\ & \frac{1}{2} g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{M^2}{2} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{M^2}{2} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\nu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\nu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 s_w (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\nu A_\nu \phi^+ \phi^- - e^2 (\gamma \partial + m_\nu^2) e^2 - e^2 \gamma \partial u_\nu^2 - \partial_\mu^2 (\gamma \partial + m_\nu^2) u_\nu^2 - \\ & \partial_\mu^2 (\gamma \partial + m_\nu^2) d_\nu^2 + ig_{s_w} A_\nu [-(e^2 \gamma^\mu e^\lambda) + \frac{2}{3} (\partial_\mu^2 \gamma^\mu u_\nu^2) - \frac{1}{3} (\partial_\mu^2 \gamma^\mu d_\nu^2)] + \\ & \frac{2e}{3c_w} Z_\mu^0 [(e^2 \gamma^\mu (1 + \gamma^5) u^\lambda) + (e^2 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\partial_\mu^2 \gamma^\mu (\frac{1}{2} s_w^2 - \\ & 1 - \gamma^5) u_\nu^2) + (\partial_\mu^2 \gamma^\mu (1 - \frac{2}{3} s_w^2 - \gamma^5) d_\nu^2)] + \frac{2e}{3c_w} W_\mu^+ [(e^2 \gamma^\mu (1 + \gamma^5) e^\lambda) + \\ & (\partial_\mu^2 \gamma^\mu (1 + \gamma^5) C_{\lambda\nu} d_\nu^2)] + \frac{2e}{3c_w} W_\mu^- [(e^2 \gamma^\mu (1 + \gamma^5) u^\lambda) + (\partial_\mu^2 \gamma^\mu C_{\lambda\nu}^- \gamma^\mu (1 + \\ & \gamma^5) u_\nu^2)] + \frac{2e}{3c_w} \frac{M^2}{2} [-\phi^+ (e^2 (1 - \gamma^5) e^\lambda) + \phi^- (e^2 (1 + \gamma^5) u^\lambda)] - \\ & \frac{2}{3} \frac{M^2}{c_w} [H (e^2 e^\lambda) + i\phi^0 (e^2 \gamma^5 e^\lambda)] + \frac{2M^2}{32c_w^2} \phi^+ [-m_\nu^2 (\partial_\mu^2 C_{\lambda\nu} (1 - \gamma^5) d_\nu^2) + \\ & m_\nu^2 (\partial_\mu^2 C_{\lambda\nu} (1 + \gamma^5) d_\nu^2)] + \frac{2M^2}{32c_w^2} \phi^- [m_\nu^2 (\partial_\mu^2 C_{\lambda\nu}^+ (1 + \gamma^5) u_\nu^2) - m_\nu^2 (\partial_\mu^2 C_{\lambda\nu}^+ (1 - \\ & \gamma^5) u_\nu^2)] - \frac{2}{3} \frac{M^2}{c_w} H (\partial_\mu^2 u_\nu^2) - \frac{2}{3} \frac{M^2}{c_w} H (\partial_\mu^2 d_\nu^2) + \frac{2}{3} \frac{M^2}{c_w} \phi^0 (\partial_\mu^2 \gamma^5 u_\nu^2) - \\ & \frac{2}{3} \frac{M^2}{c_w} \phi^0 (\partial_\mu^2 \gamma^5 d_\nu^2) + \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + \bar{X}^0 (\partial^\mu - \\ & \frac{M^2}{c_w}) X^0 + \bar{Y} \partial^\mu Y + ig_{c_w} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\mu \bar{Y} X^- - \\ & \partial_\mu \bar{X}^+ Y) + ig_{c_w} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig_{s_w} W_\mu^- (\partial_\mu \bar{X}^- Y - \\ & \partial_\mu \bar{Y} X^+) + ig_{c_w} Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig_{s_w} A_\mu (\partial_\mu \bar{X}^+ X^+ - \\ & \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H] + \\ & \frac{1-2s_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^- - \bar{X}^- X^0 \phi^+] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+] + \\ & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} ig M [\bar{X}^+ X^+ \phi^- - \bar{X}^- X^- \phi^0]. \end{aligned}$$

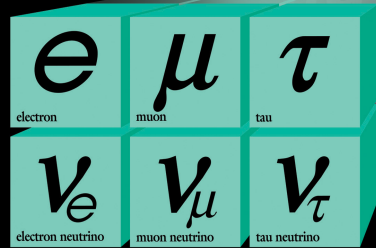
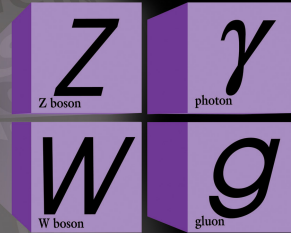
Standard Model is **extraordinarily predictive**, but is only mathematically consistent with **massless** exchange particles

We know the  $W^\pm$  and  $Z^0$ , and others, have (even very large) masses

# Quarks



# Forces



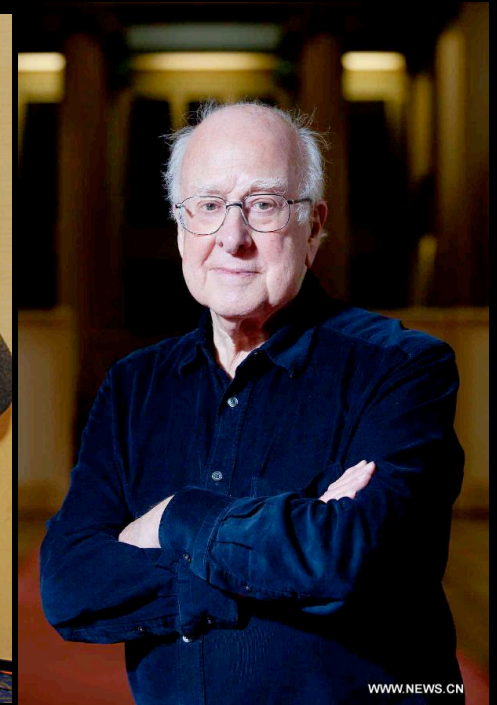
# Leptons

Overcome by “Higgs Mechanism”

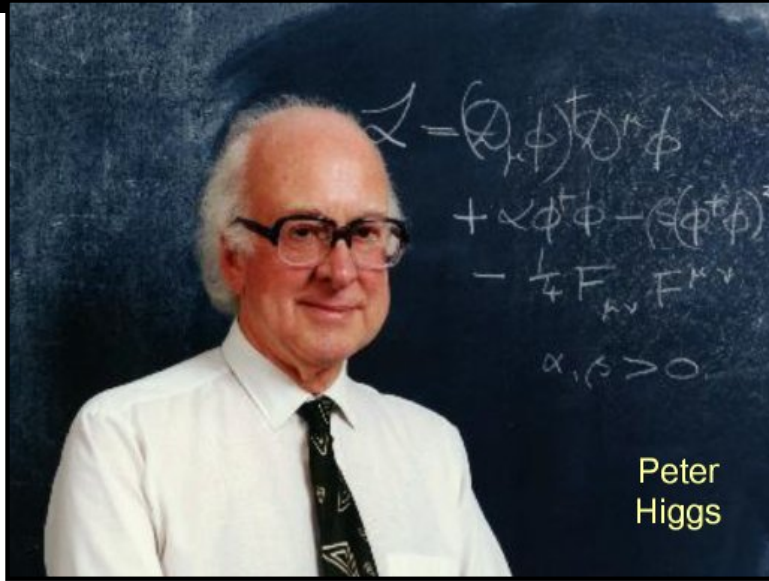
There is **something new** in the Universe, a “field” (named after Peter Higgs) and the various particles interact differently with Higgs field

—> **mass** is proportional to **coupling strength**

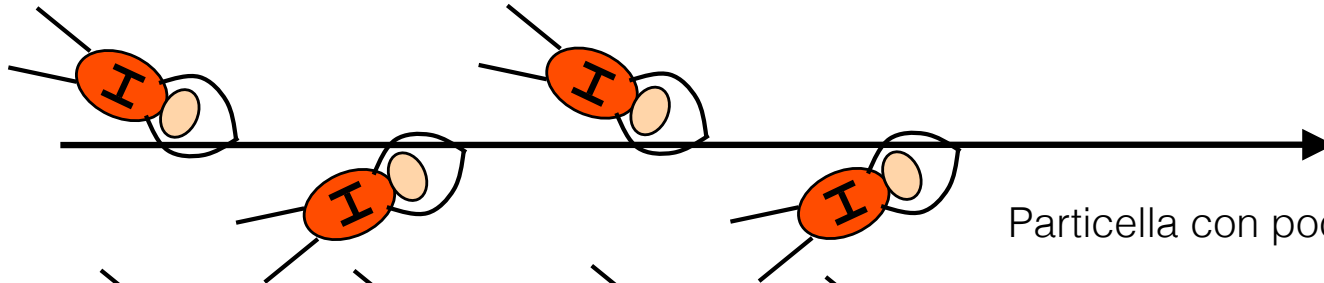
Proposed in 1964 by  
Robert Brout and  
François Englert  
Peter Higgs  
Gerald Guralnik, C.  
Richard Hagen, and Tom  
Kibble



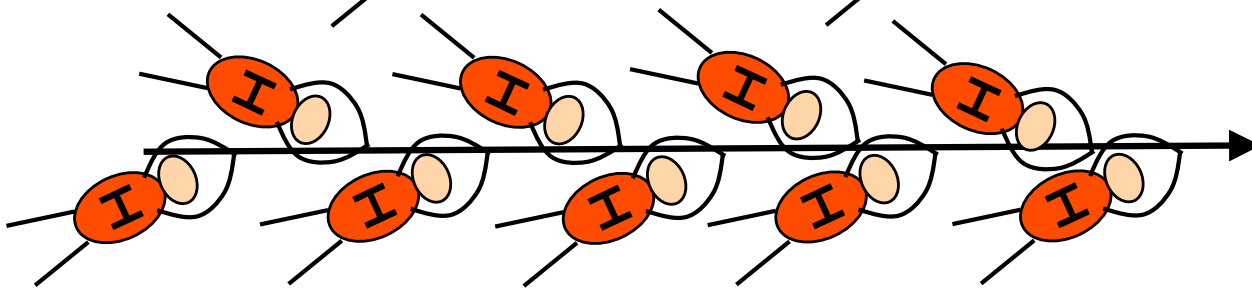
Kibble, Guralnik, Hagen, Englert, Brout and Higgs



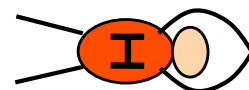
Particella senza massa - si muove alla velocità della luce



Particella con poca massa - si muove più lentamente

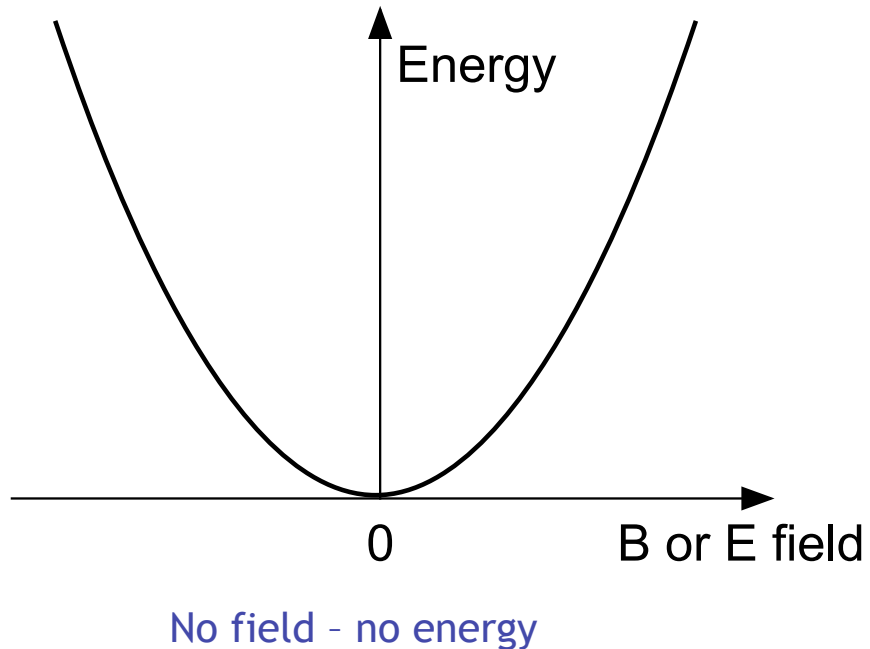


Particella con molta massa - si muove ancora più lentamente



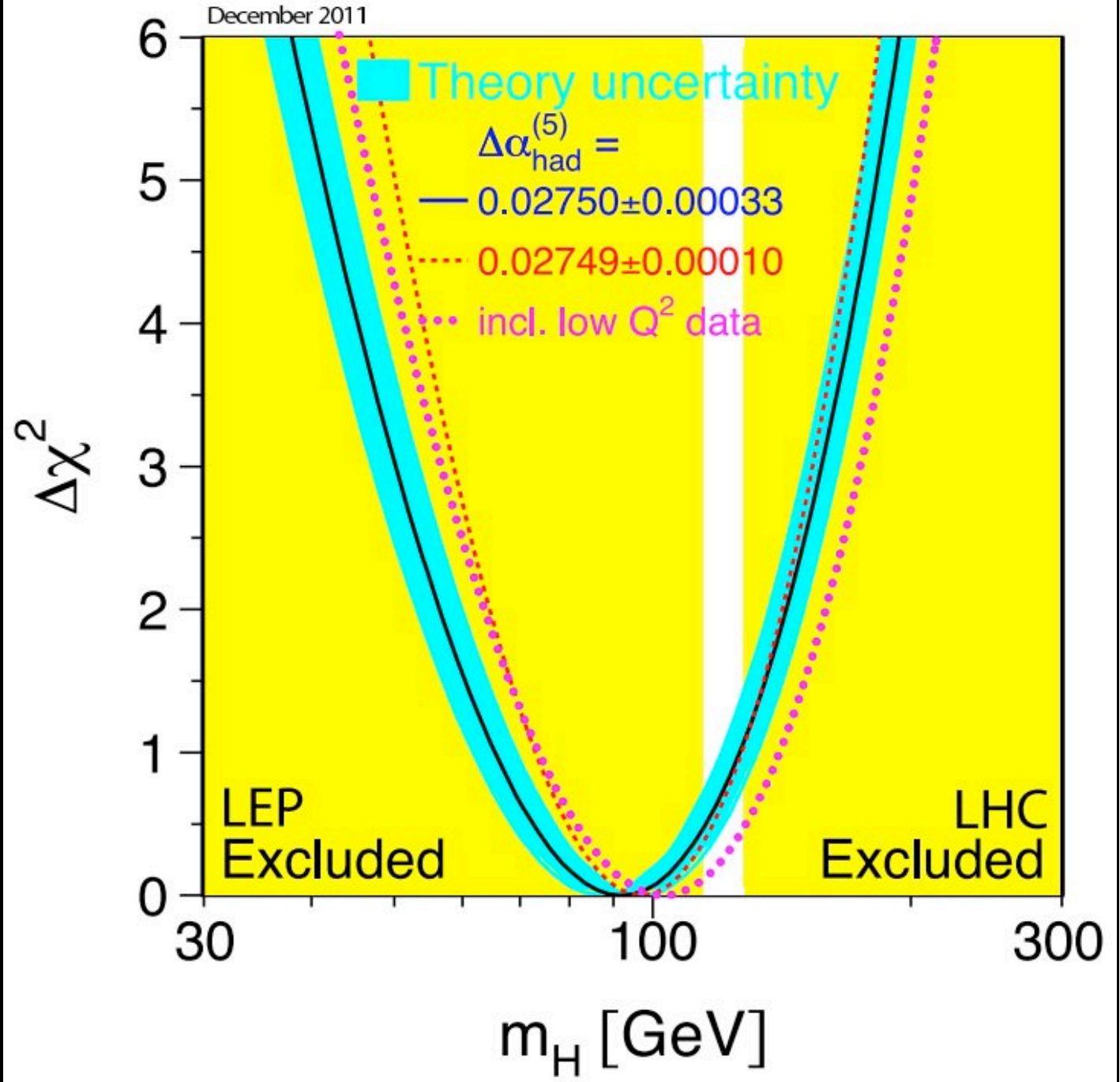
Con energia sufficiente, si dovrebbe poter produrre una particella libera di Higgs

In Electromagnetism each point in space has an associated value (and direction) of the B and E fields



Field is manifested by a particle: the “Higgs boson”

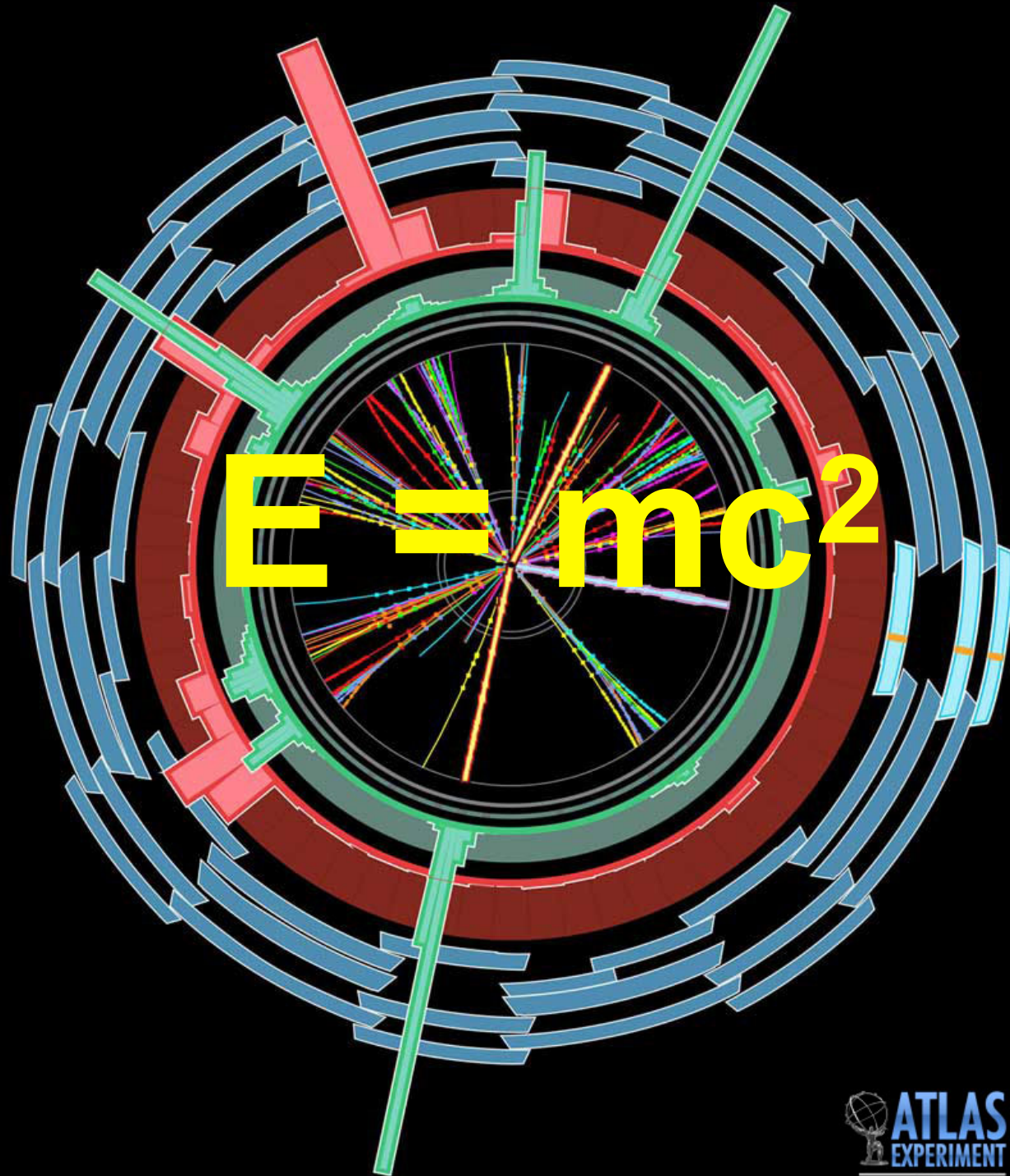
Theory prediction,  
as of December 2011



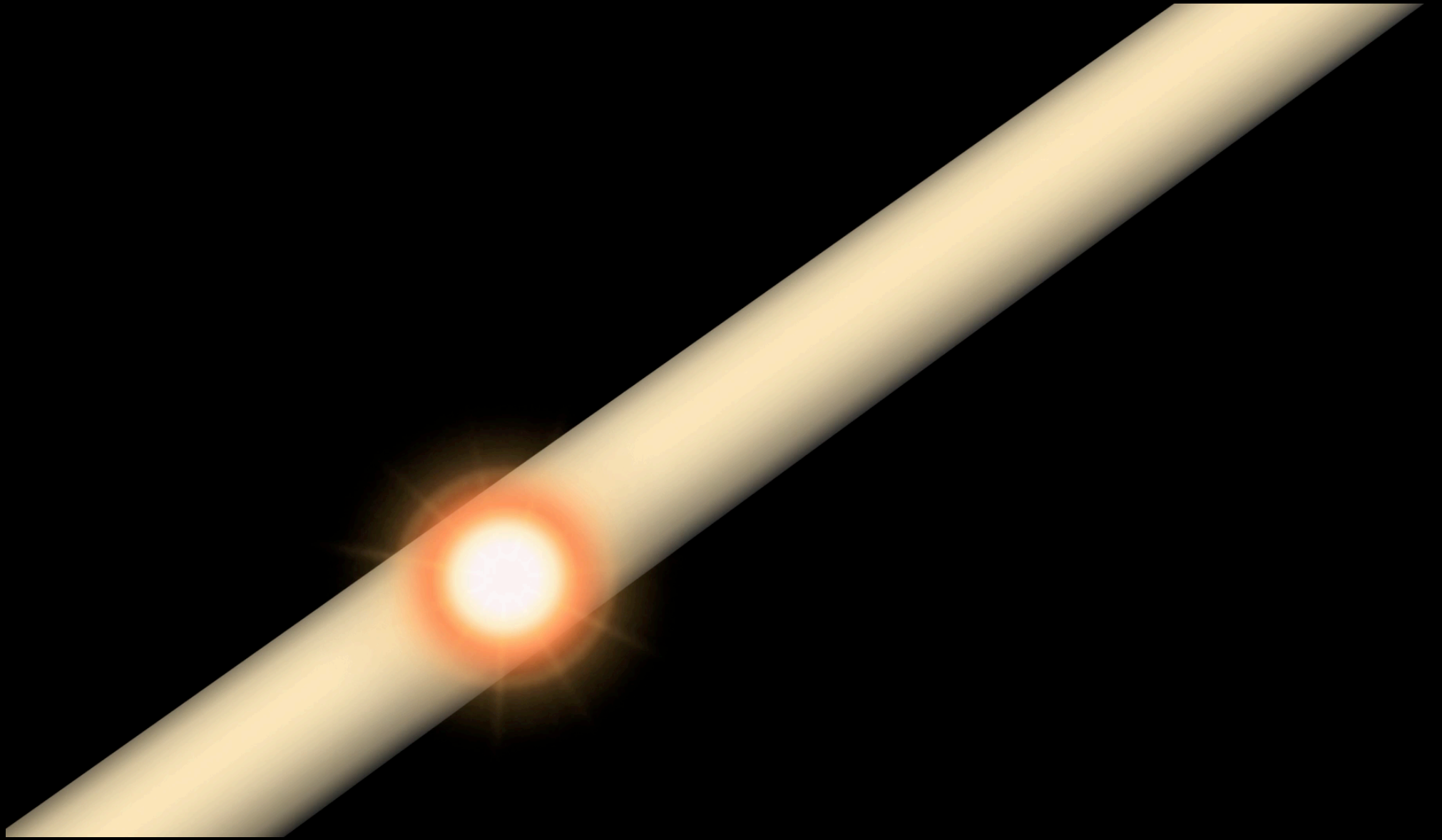
Everything ruled out except  $115 < M_H < 130 \text{ GeV}/c^2$

## **PART 3**

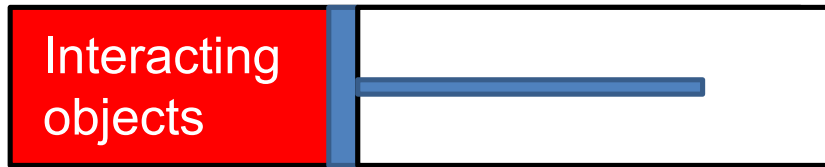
A Machine Powerful Enough /  
Window to the Early Universe



$$E = mc^2$$



## Analogy



Compress : Heat  
more dense



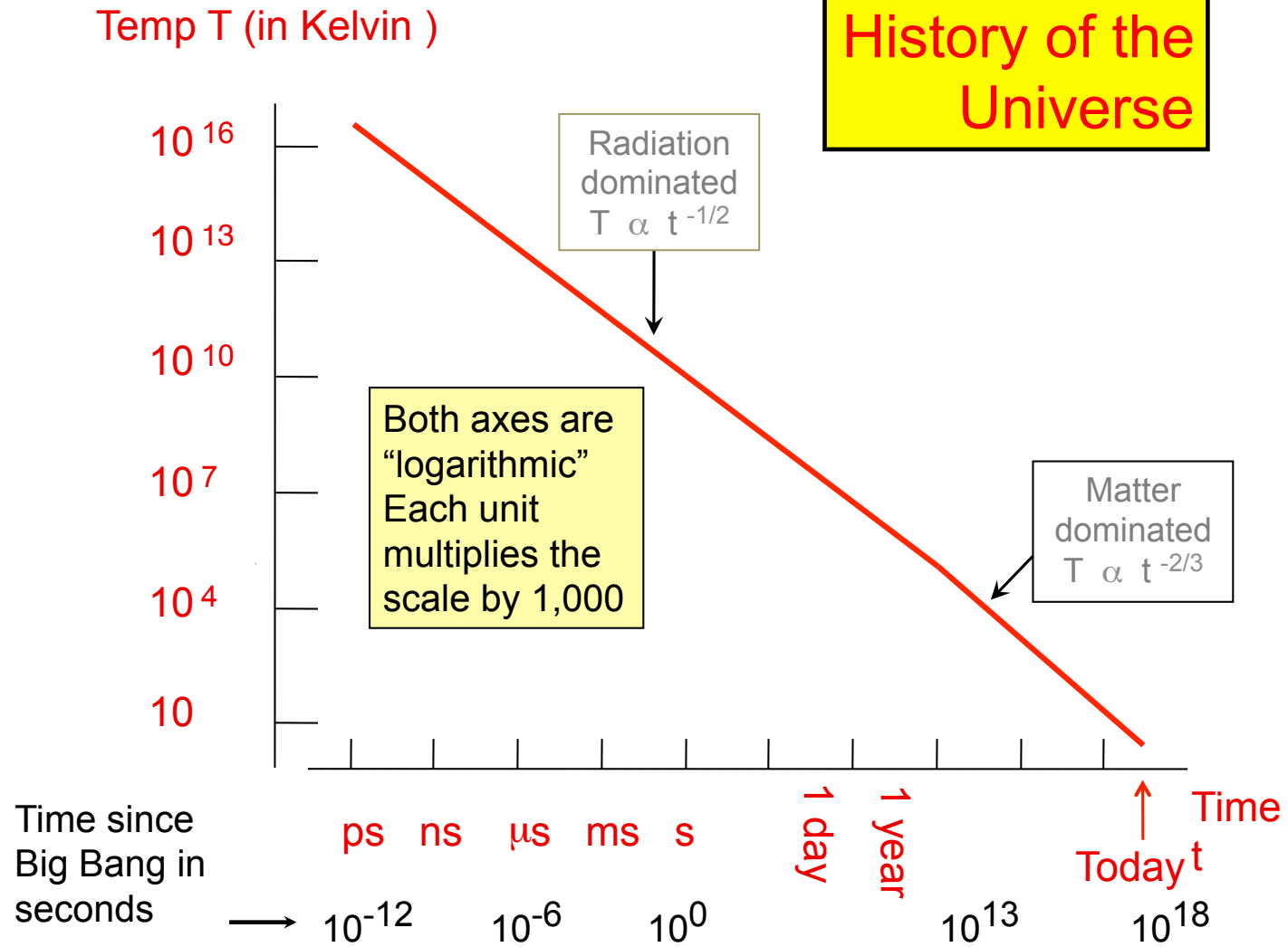
Expand : Cool  
less dense

Universe is expanding → Cooling

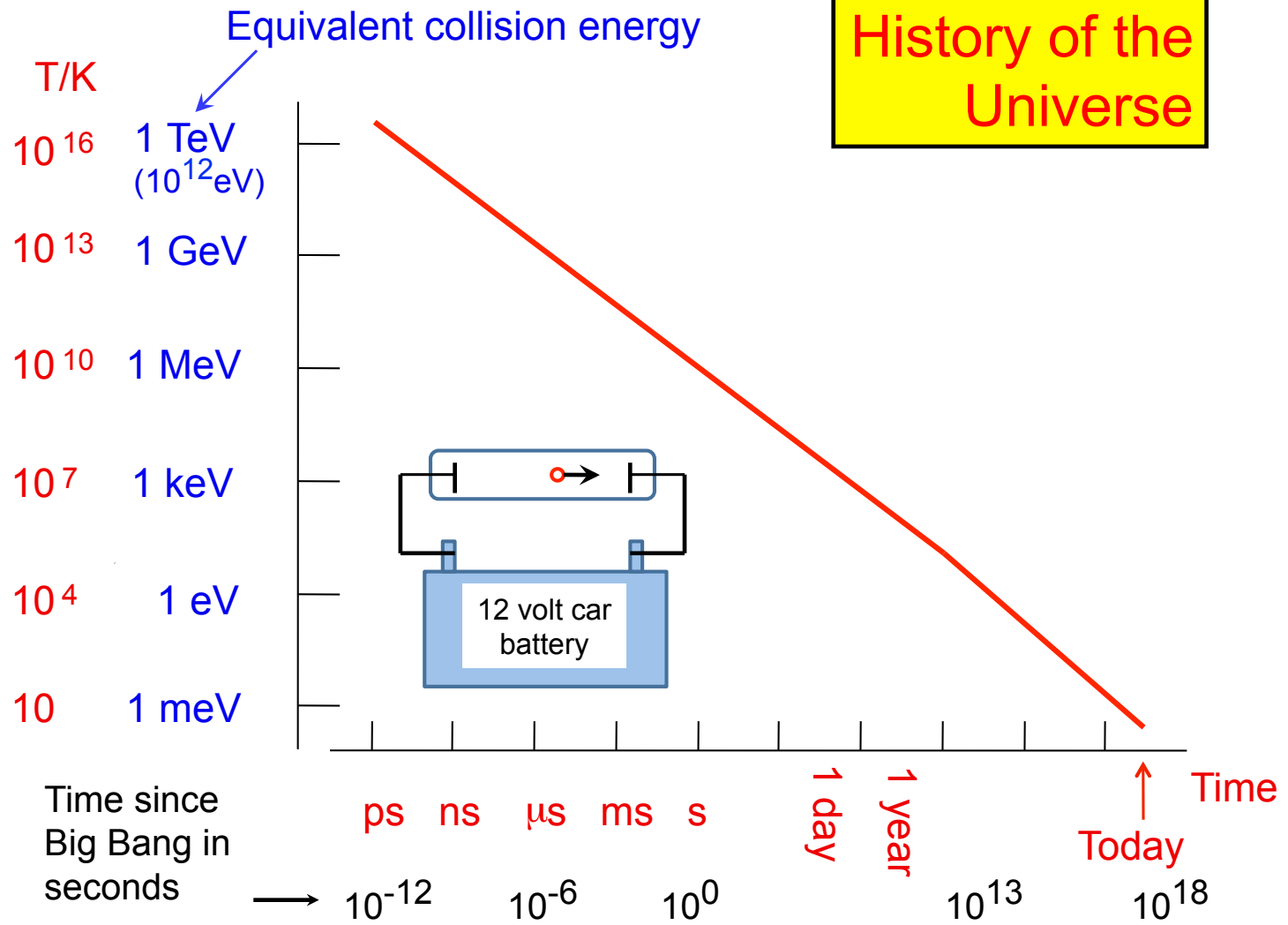
In the past → Universe was hotter

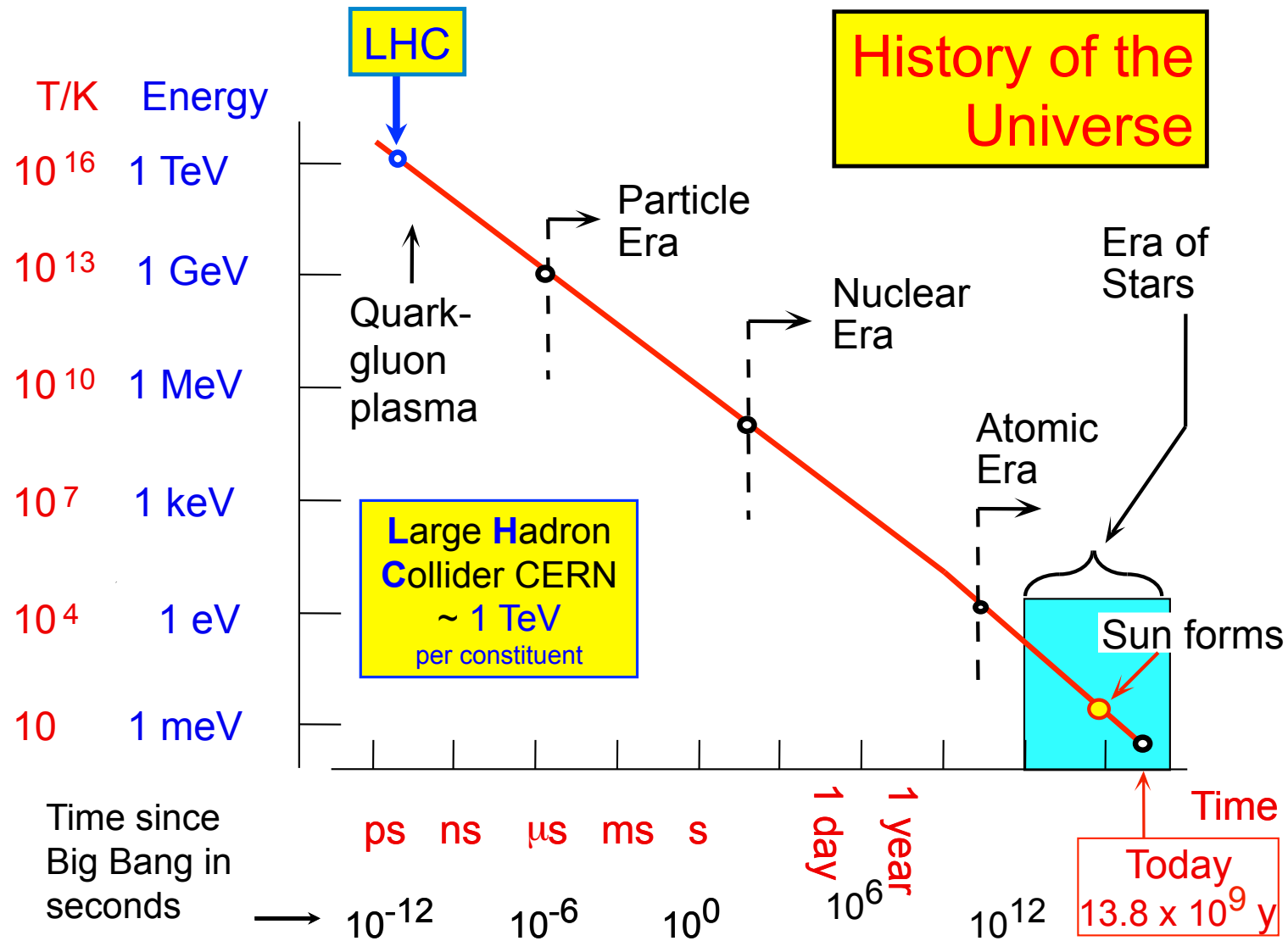
Hot Big Bang Model

# History of the Universe

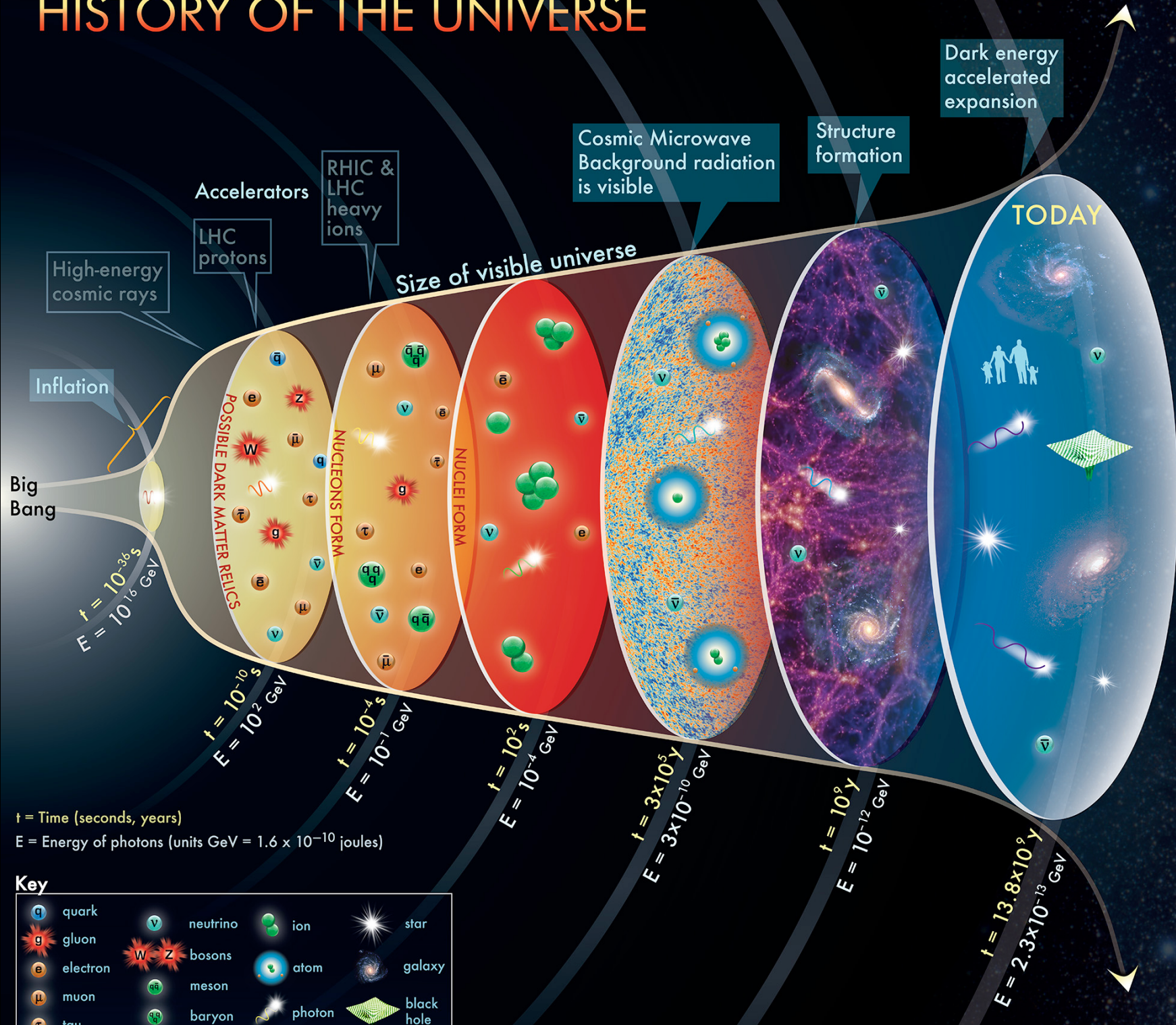


# History of the Universe





# HISTORY OF THE UNIVERSE



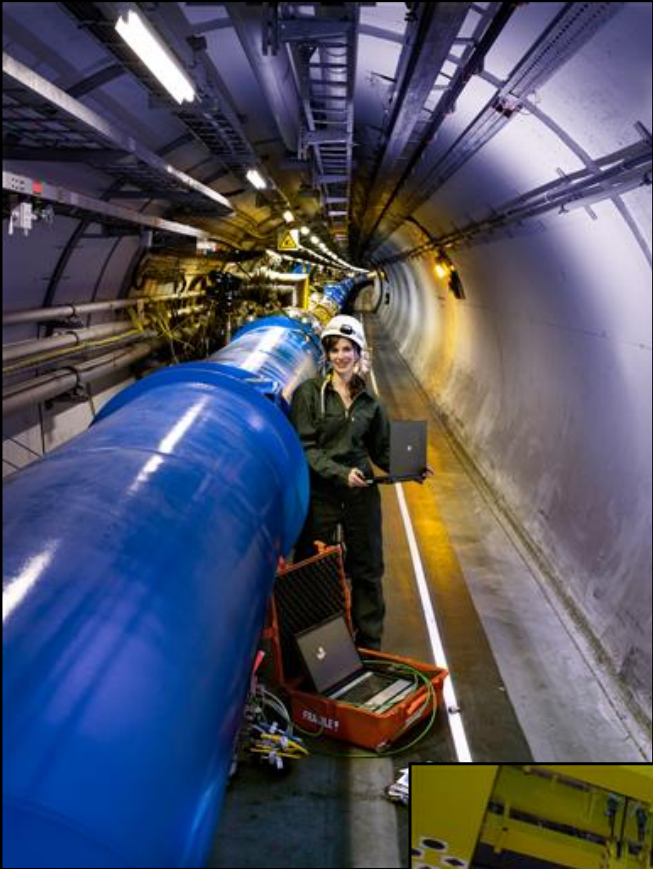
t = Time (seconds, years)  
E = Energy of photons (units GeV =  $1.6 \times 10^{-10}$  joules)

**Key**

quark	neutrino	ion	star
gluon	bosons	atom	galaxy
electron	meson	photon	black hole
muon	baryon		
tau			

# Building the LHC

Superconducting Magnets  
Superfluid Helium  
(Quantum liquid)





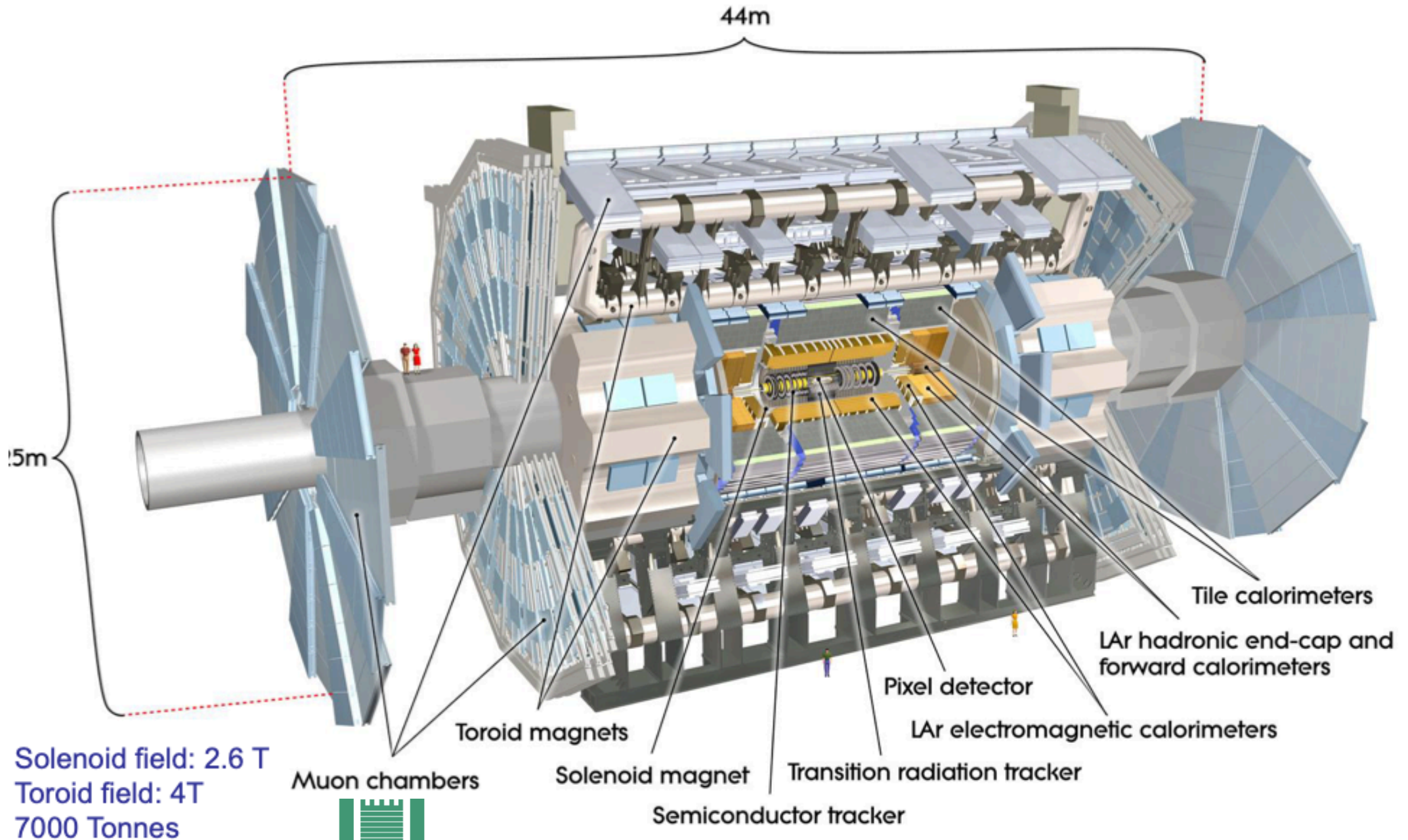
**8.36 Tesla, 100,000 times the Earth's magnetic field**  
**>1200 dipole magnets**

1.9 K, <300° C below room temperature

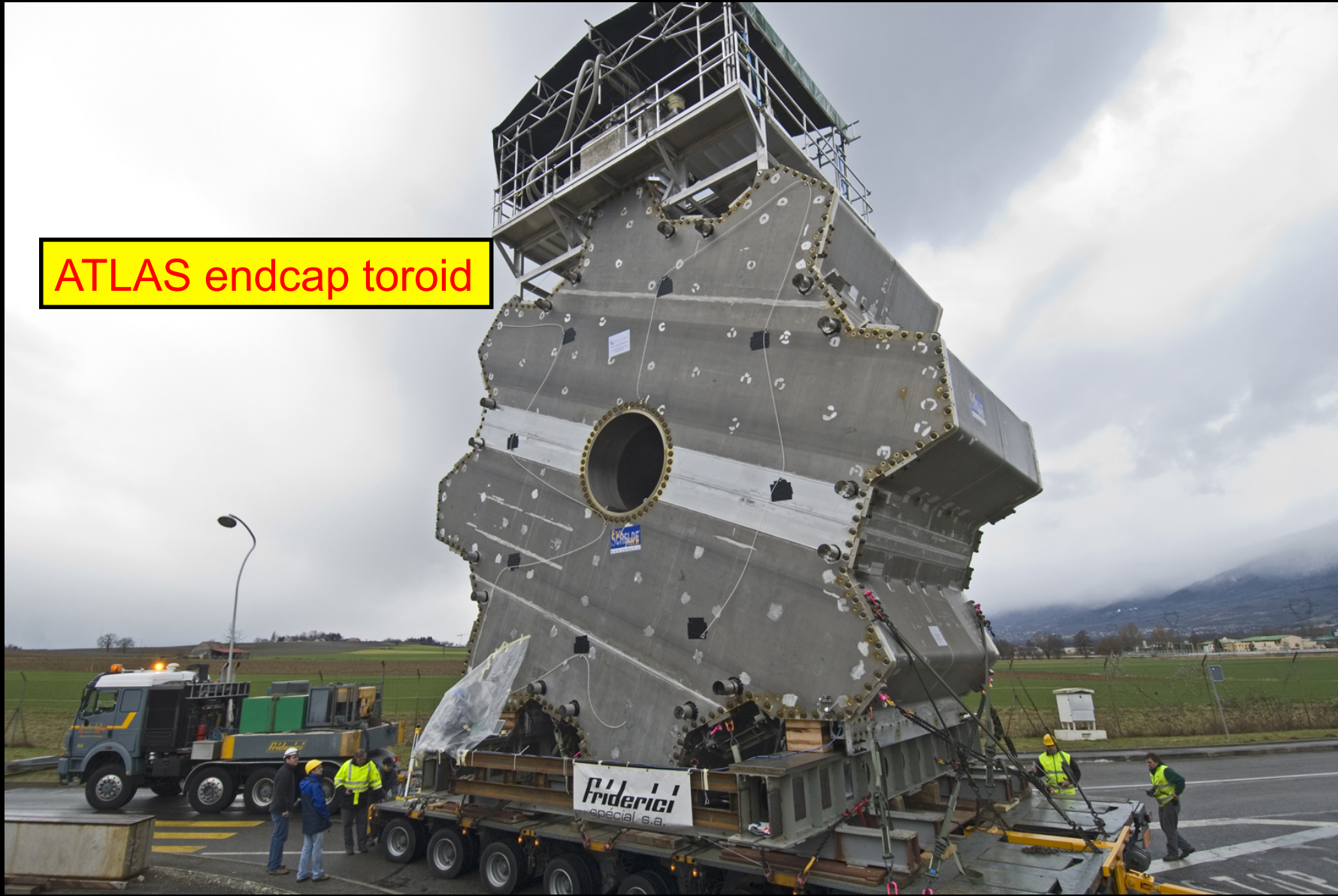
Maximum proton energy: 7 TeV    Collision Energy: 14 TeV

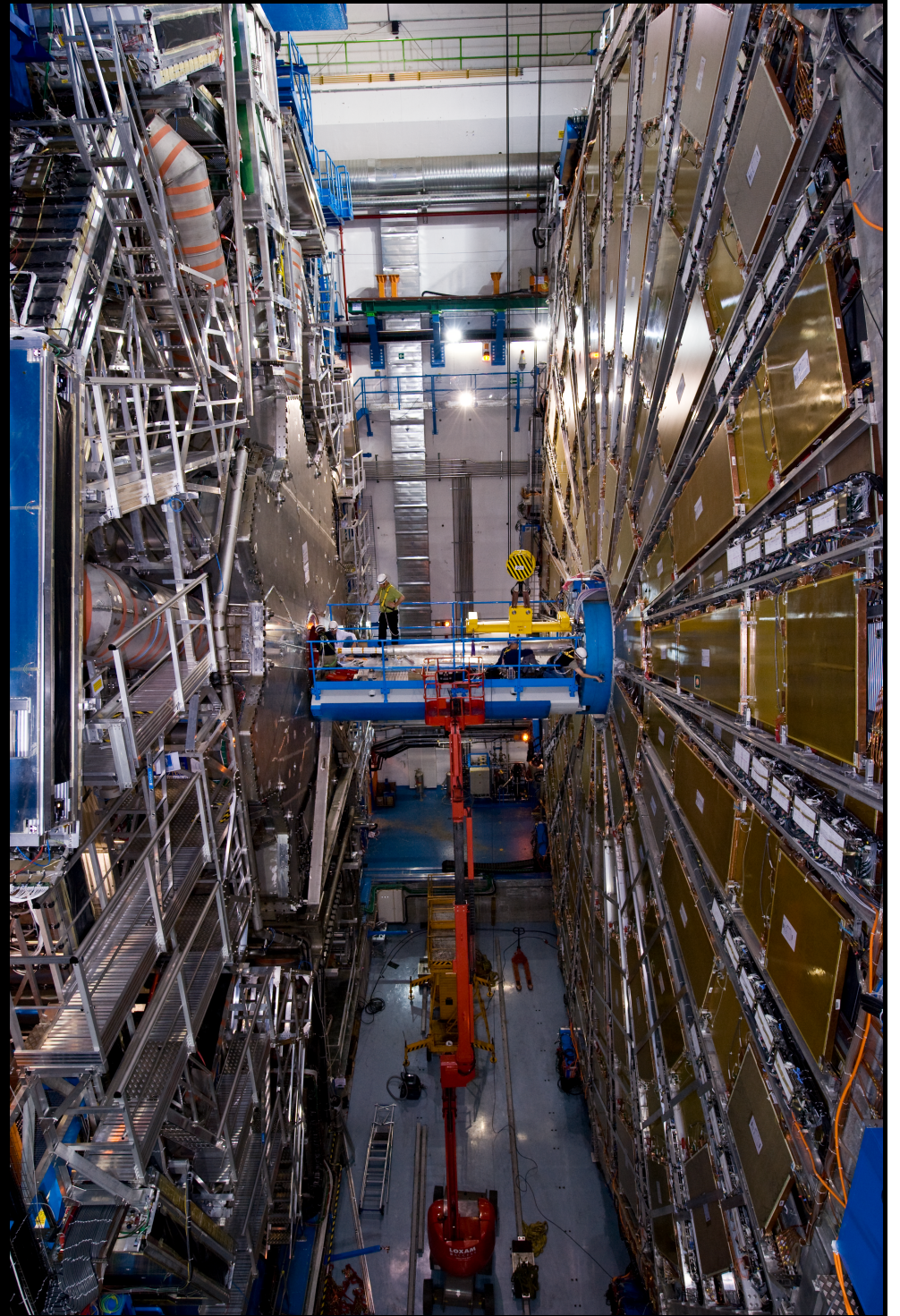
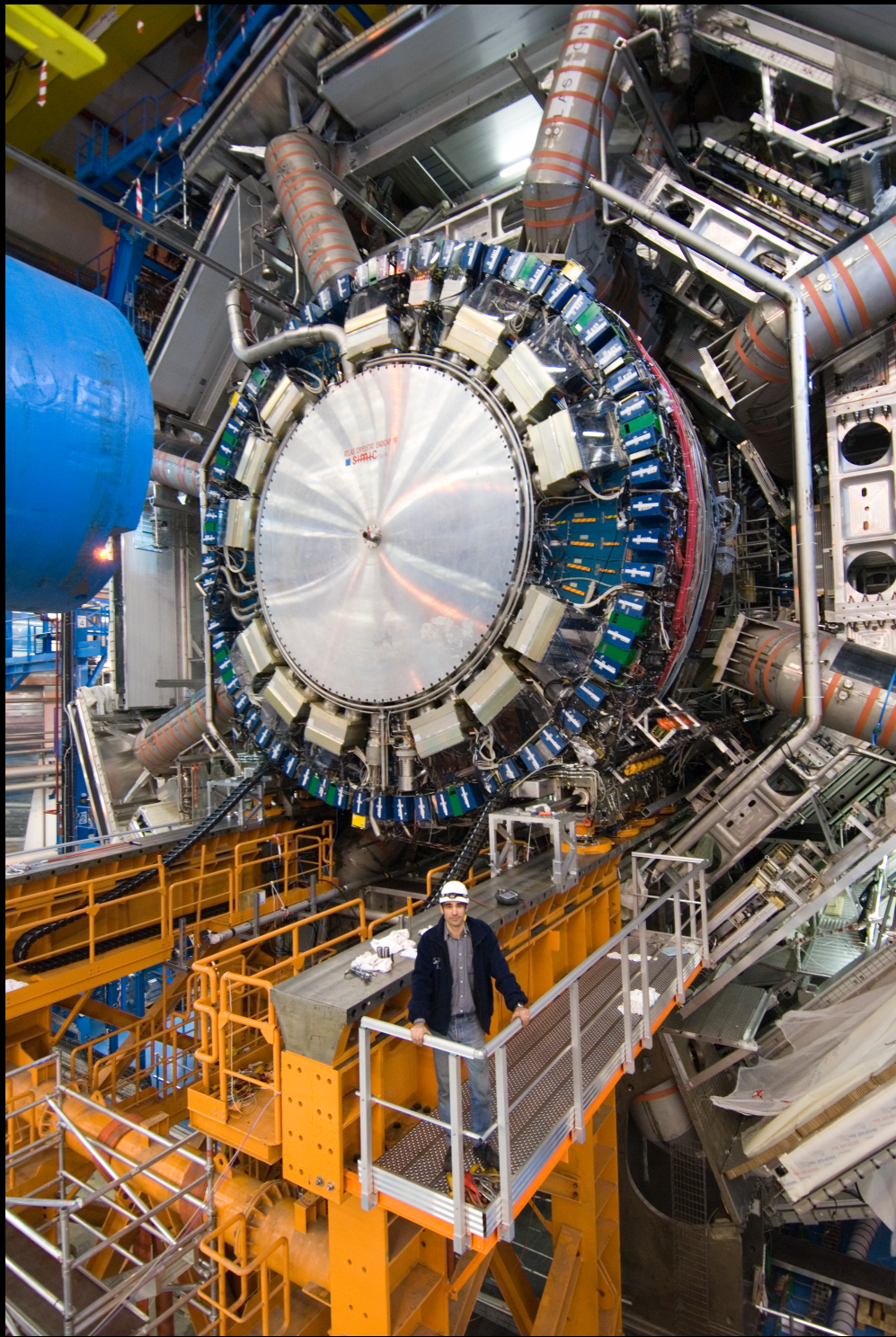
Equivalent to: 14 000 000 000 000 - 1V batteries

Looking down to dimensions of  $\sim 10^{-20}$  m



ATLAS endcap toroid





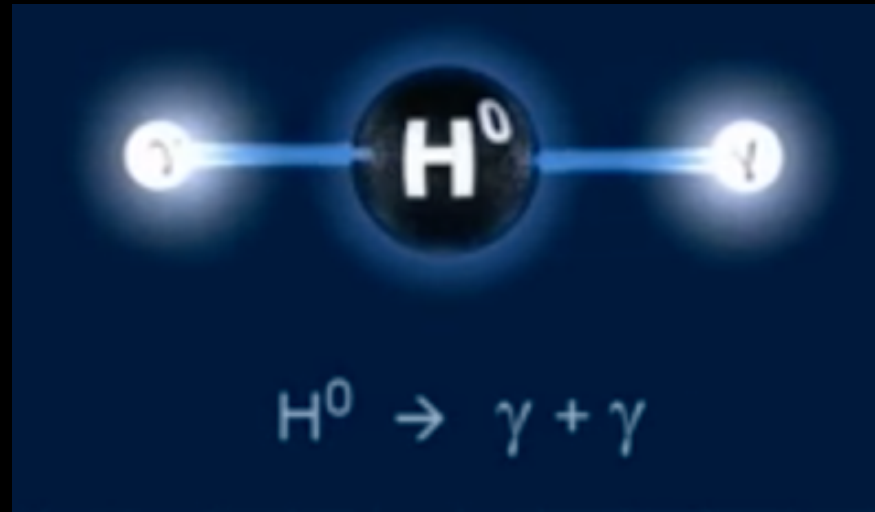


- Argentina
- Armenia
- Australia
- Austria
- Azerbaijan
- Brazil
- Canada
- Chile
- China
- Colombia
- Czech Republic
- Denmark
- France
- Georgia
- Germany
- Greece
- Israel
- Italy
- Japan
- Mongolia
- Morocco
- Netherlands
- Norway
- Palestine
- Philippines
- Poland
- Portugal
- Romania
- Serbia
- Slovakia
- Slovenia
- South Africa
- Spain
- Sweden
- Switzerland
- Taiwan
- Türkiye
- UAE
- UK
- USA
- CERN
- JINR

# ATLAS Collaboration

*177 institutions (243 institutes) from 40 countries*

$$E = \sqrt{(\vec{p}c)^2 + (m_0c^2)^2}$$



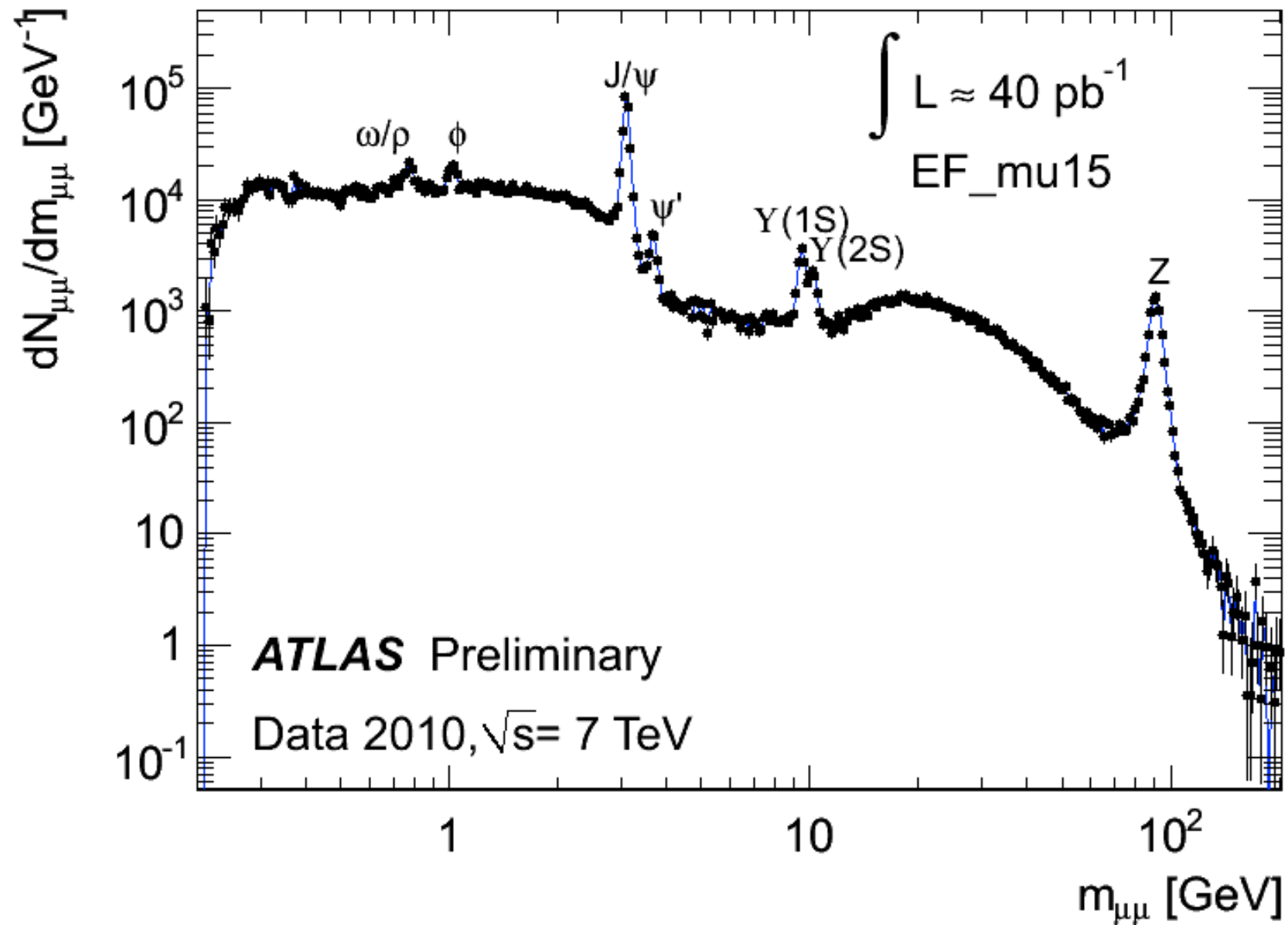
$$m_0 = \sqrt{\left(\frac{E}{c^2}\right)^2 - \left(\frac{\vec{p}}{c}\right)^2}$$

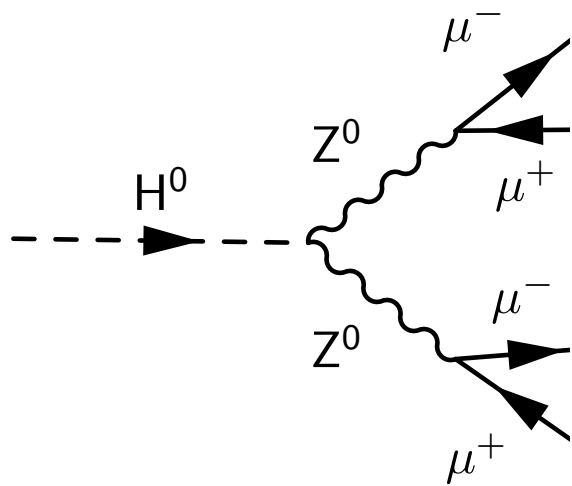
1963

1974

1977

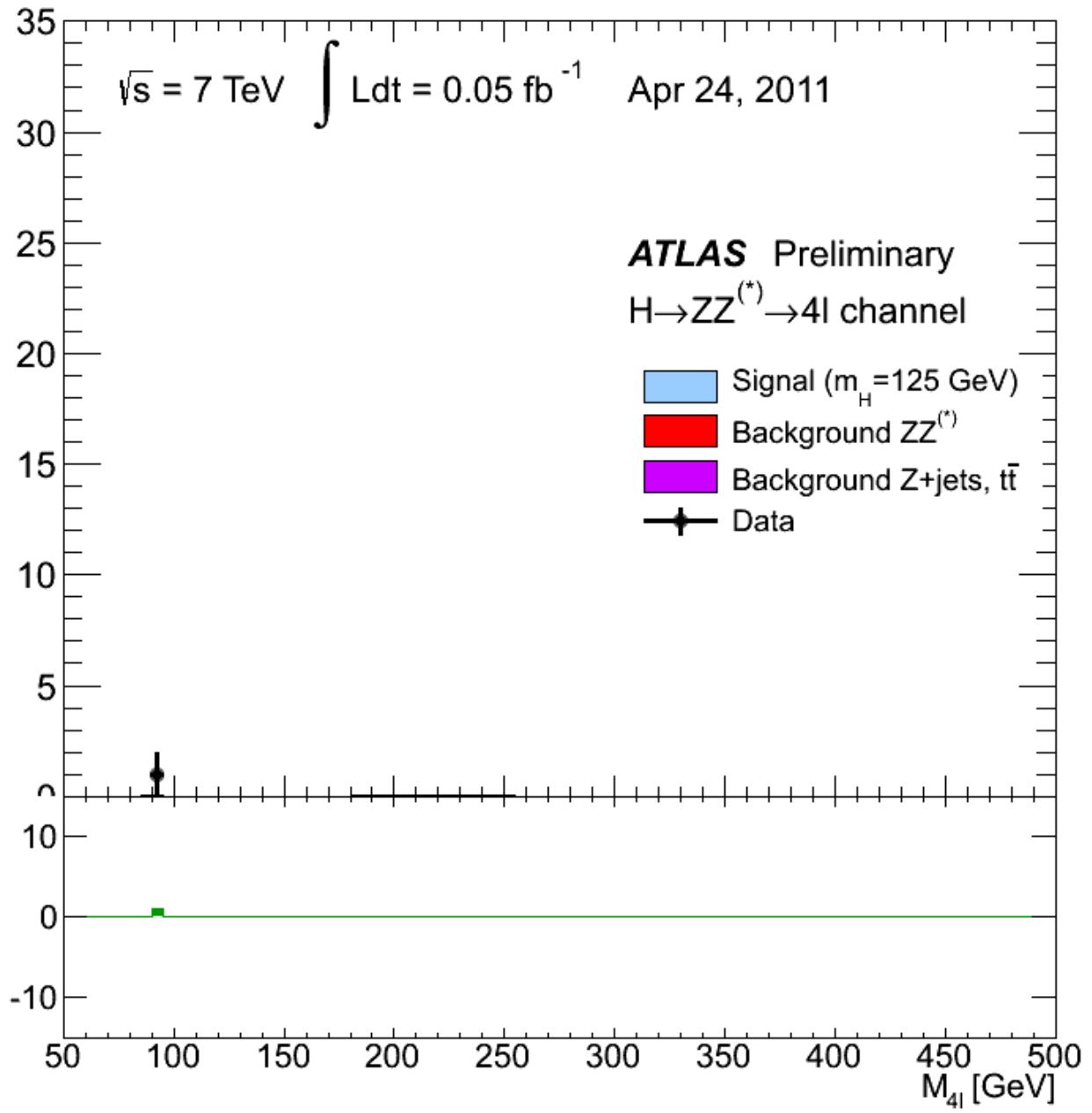
1983

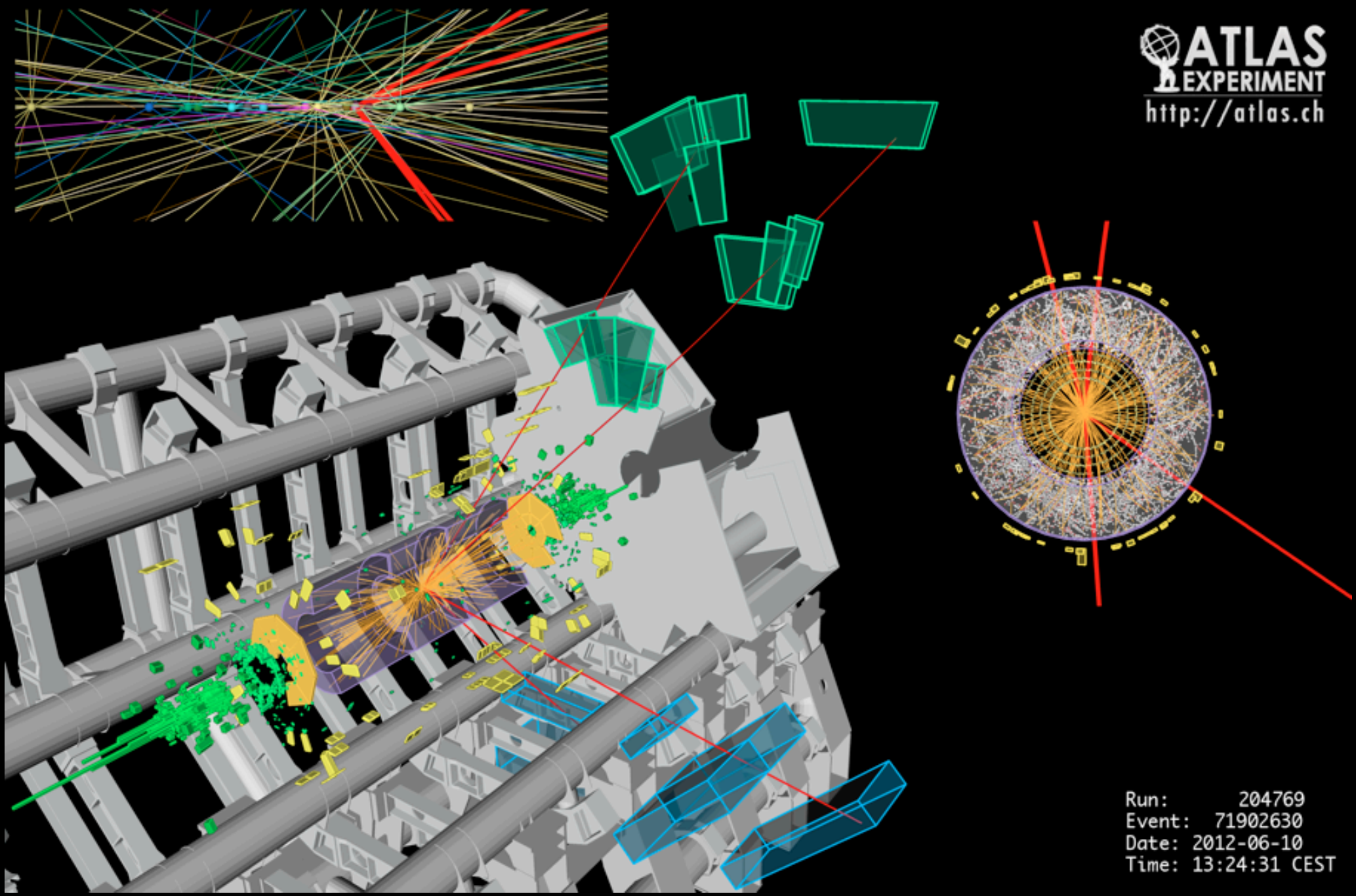




Events / 5 GeV

Data - Background

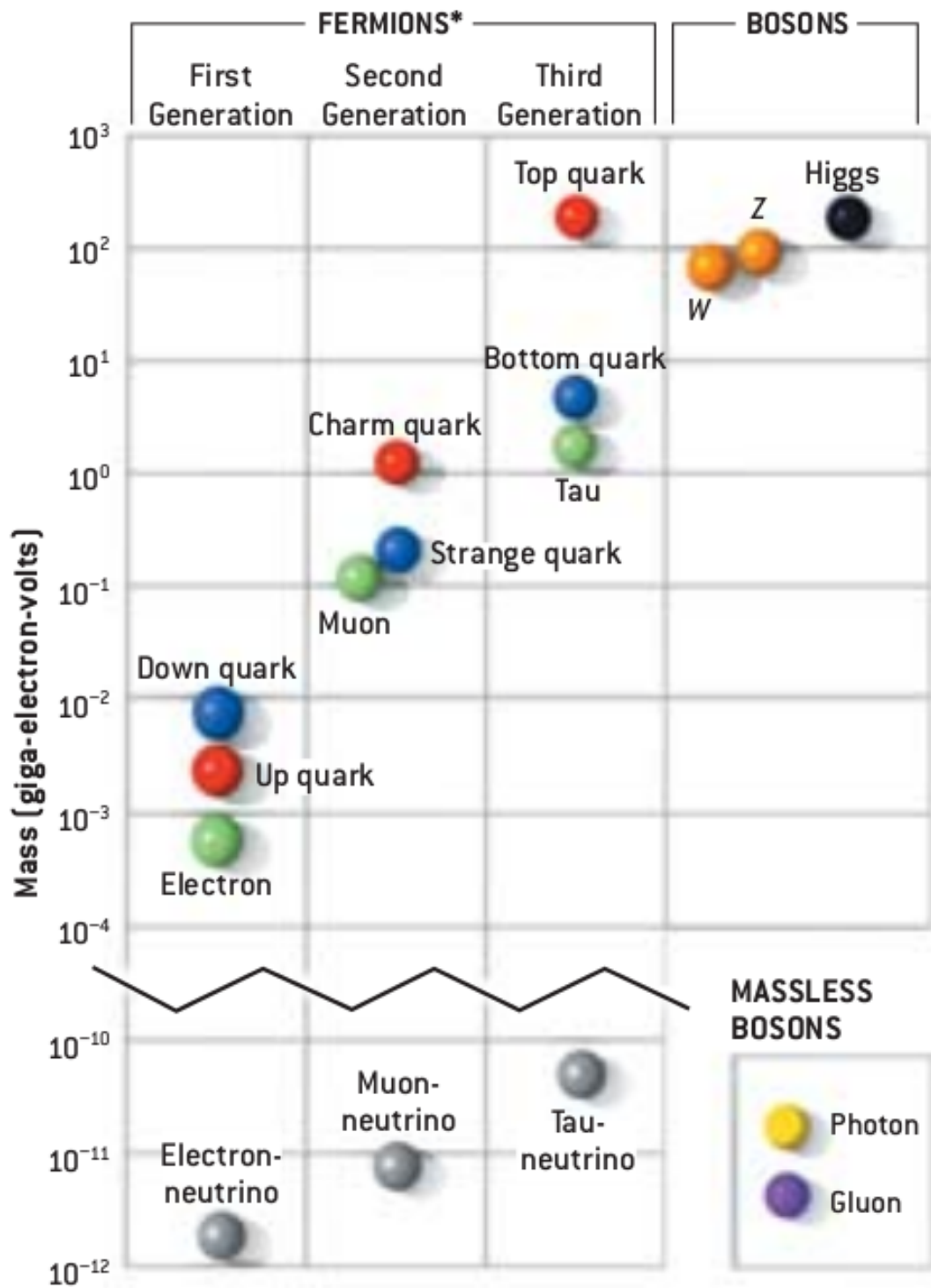






## **PART 4**

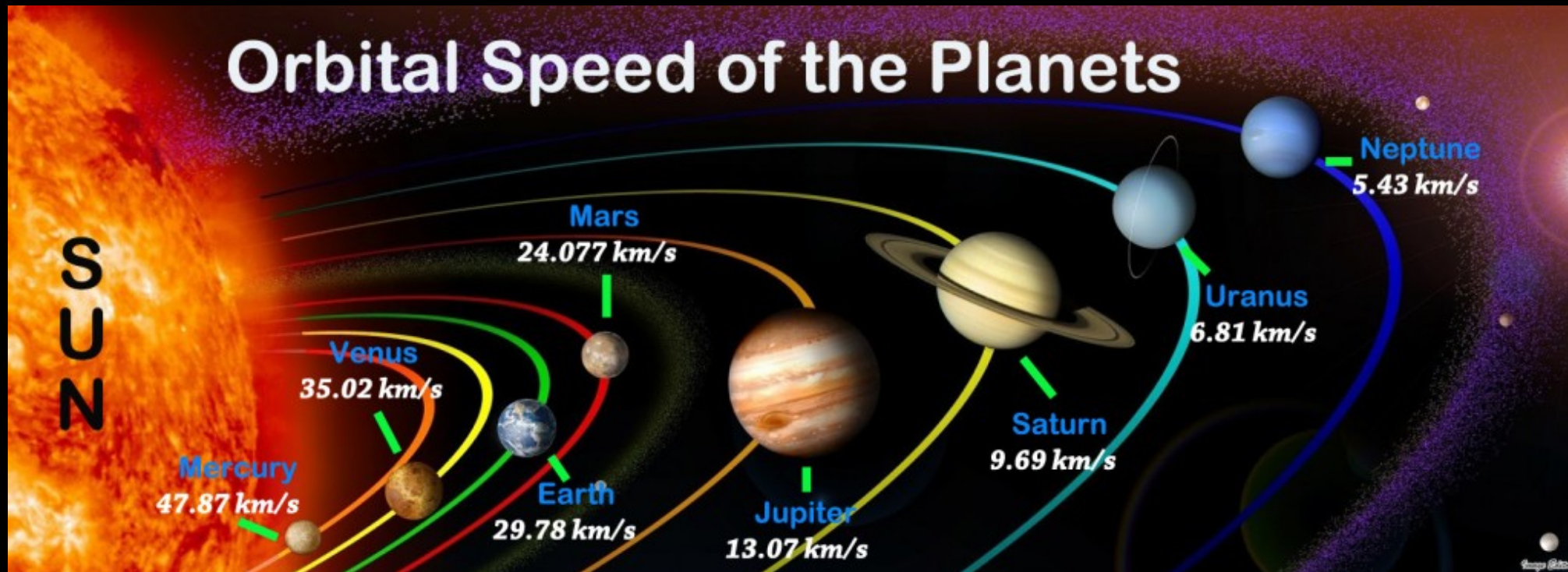
One Answer, More Questions:  
the disappeared, the invisible, the  
unexpected.



We don't understand why such value of masses ...

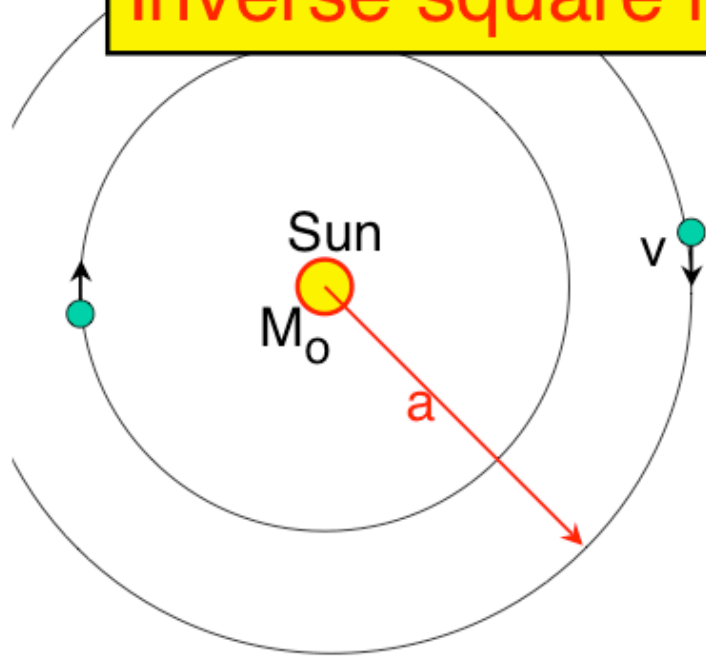


# Orbital Speed of the Planets



# What Keeps Galaxies Together ?

Inverse square law

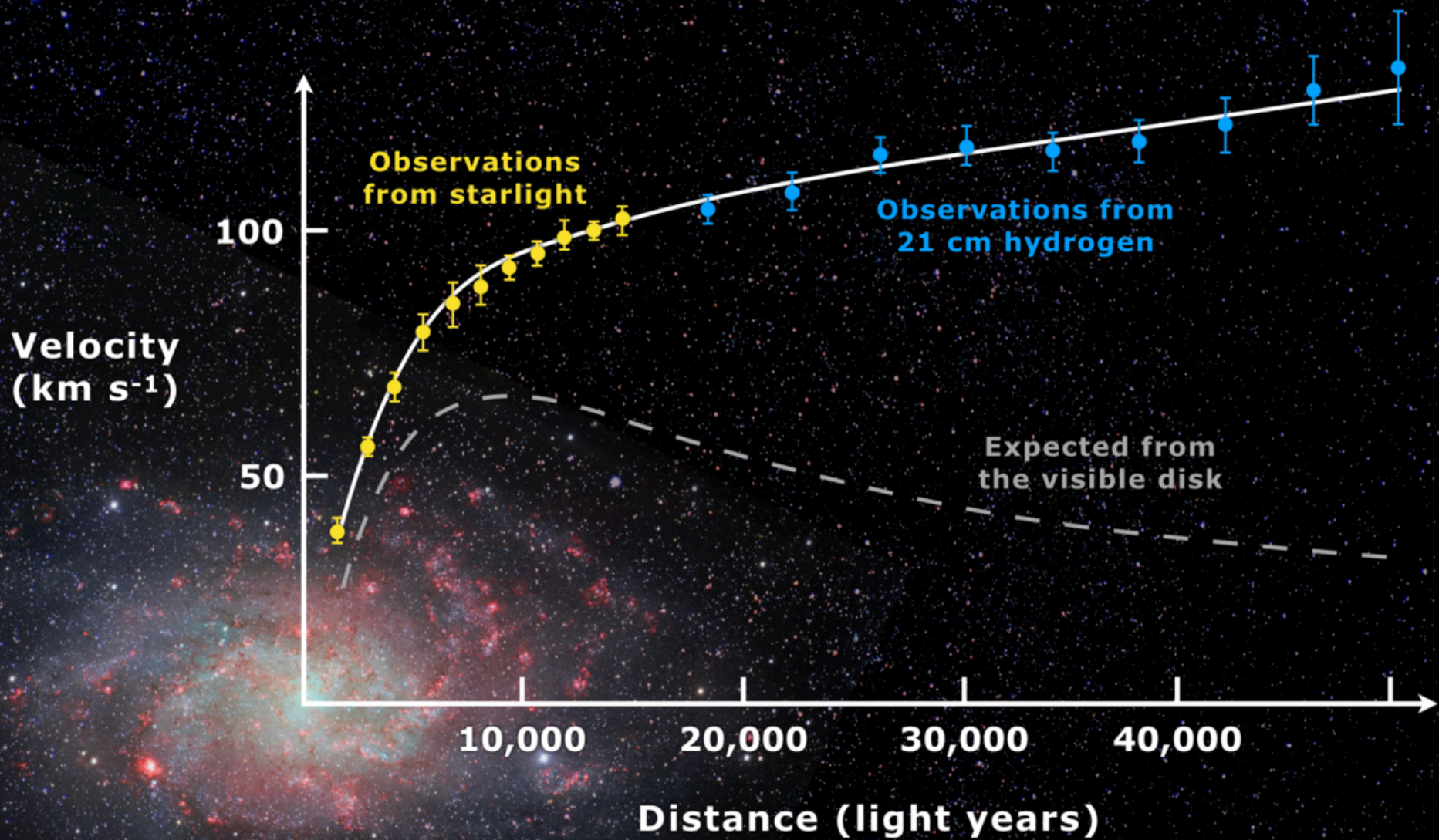


Rotation in spiral galaxies

Kepler, Newton

$$T^2 = 4 \pi^2 a^3 / G M_0$$
$$v^2 = G M_0 / a \text{ (circular orbit)}$$





Hence there is more gravitationally attractive material than is being detected:

“DARK MATTER”

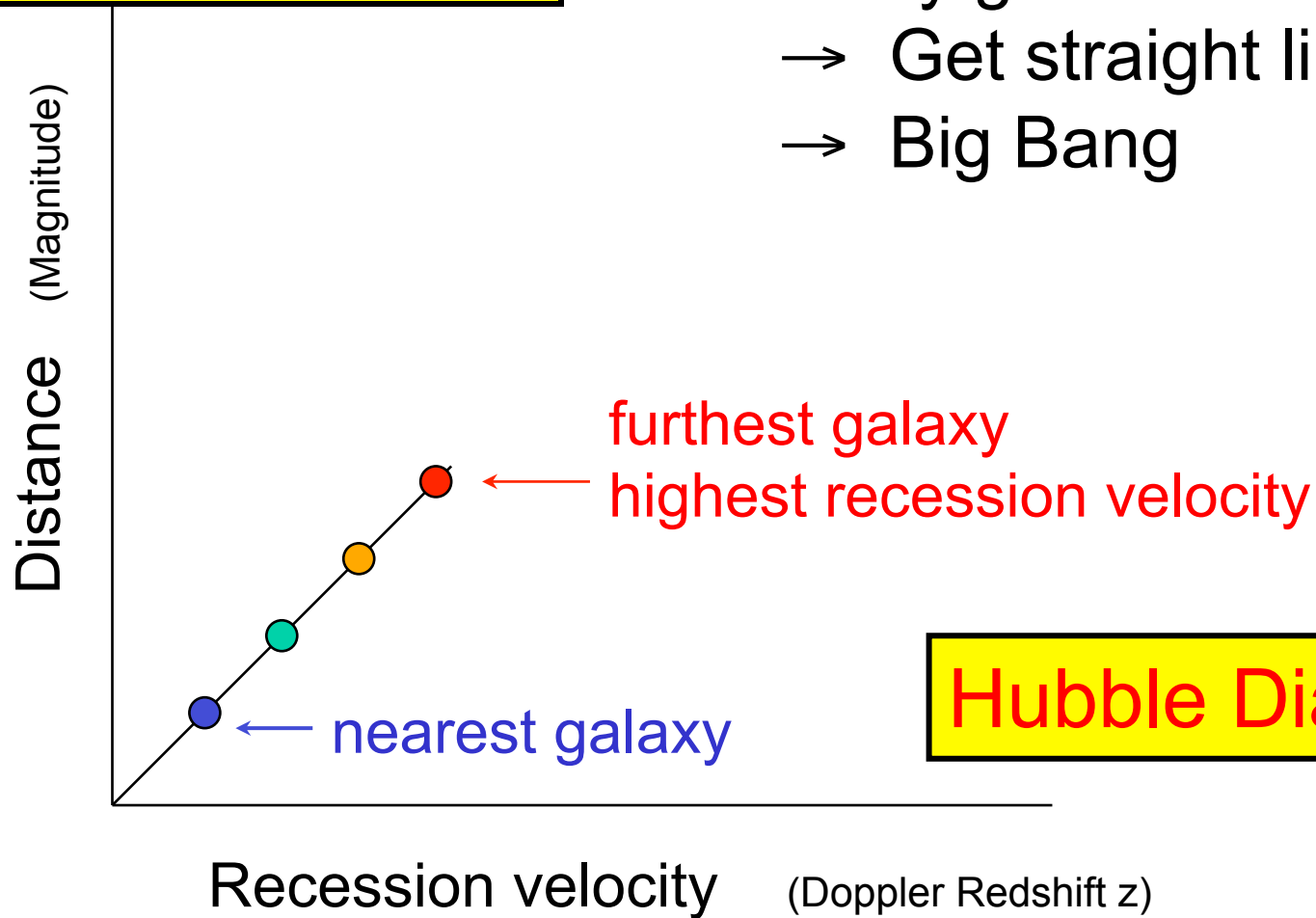
5:1



The Universe  
is like this !

Plot distance against  
recession velocity for  
many galaxies

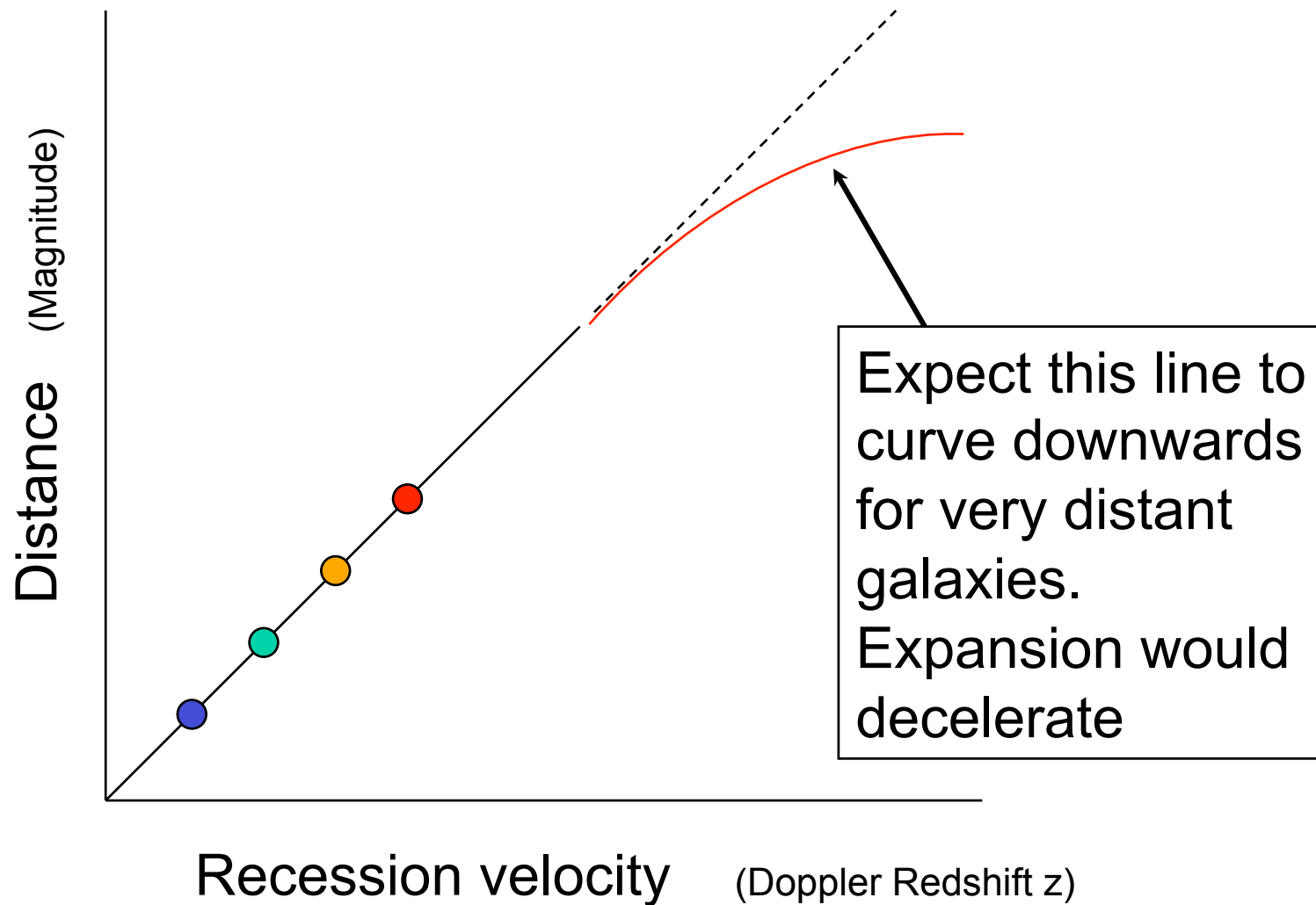
- Get straight line
- Big Bang



Hubble Diagram

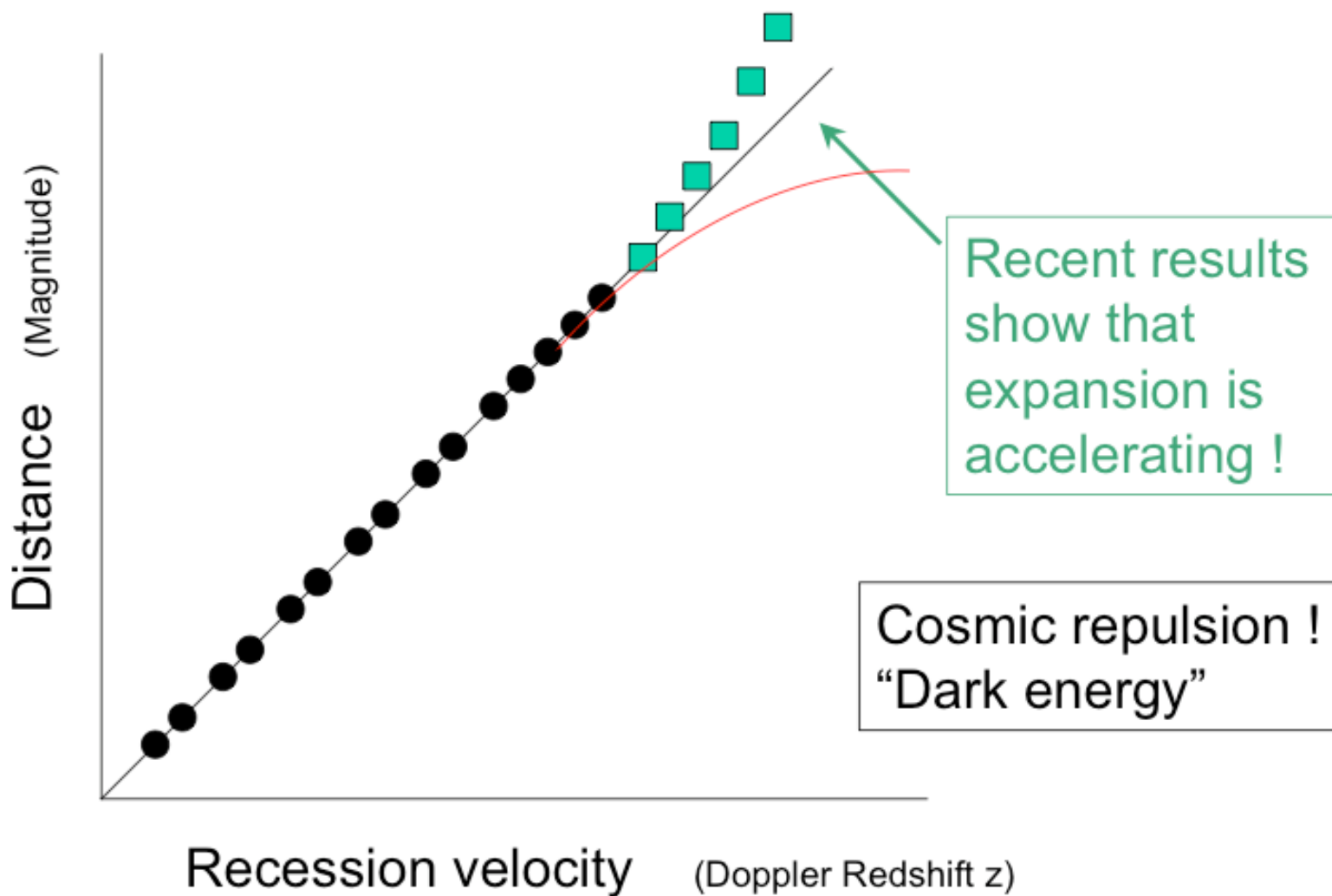
# Hubble Diagram

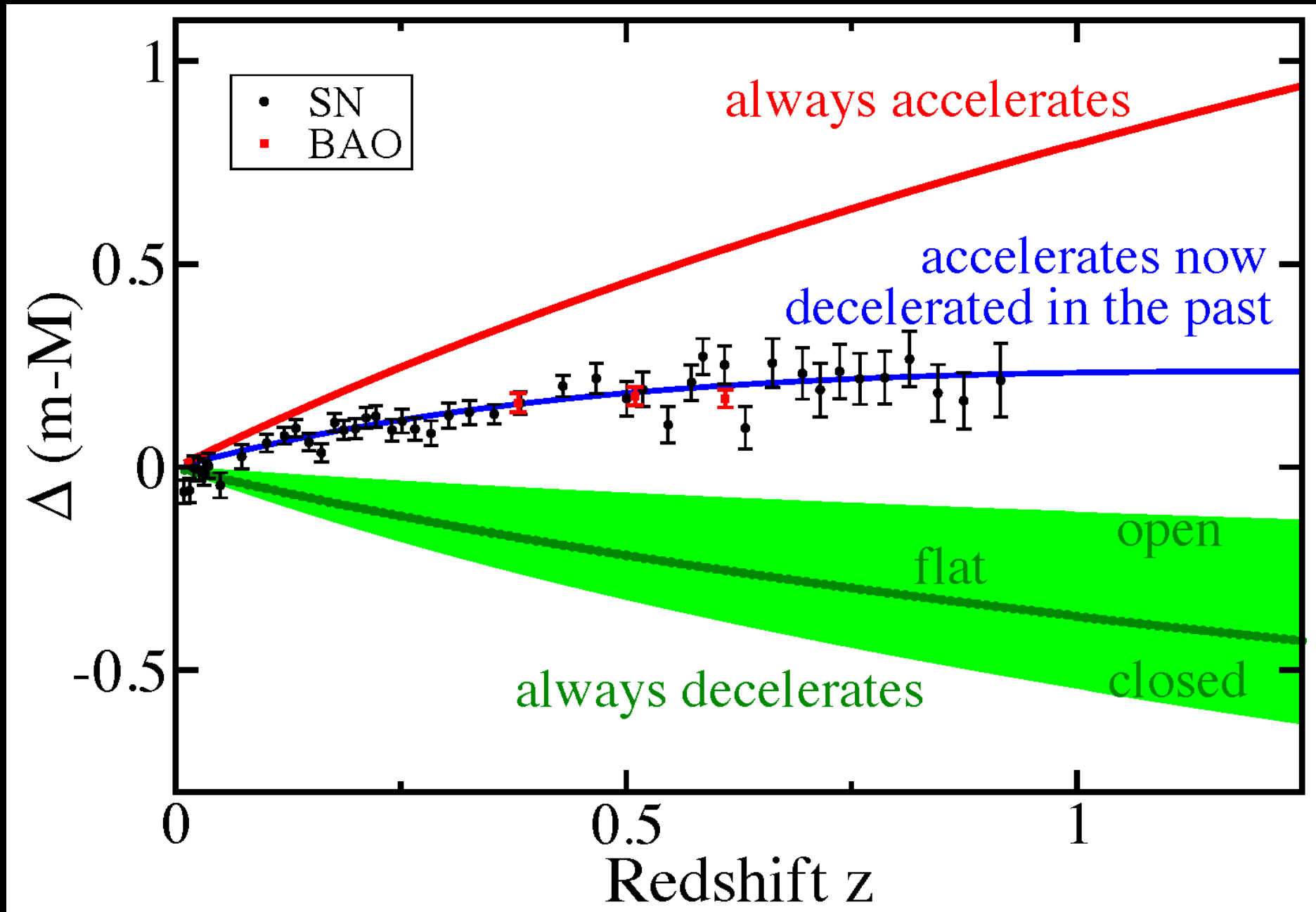
But cannot ignore gravity  
which slows down the flow



# Hubble Diagram

(simplified)





D. Huterer and D.L. Shafer, "Dark energy two decades after: Observables, probes, consistency tests" Rep. Prog. Phys., 2017

# SUMMARY

## Composition of the Universe

Dark matter  
27%



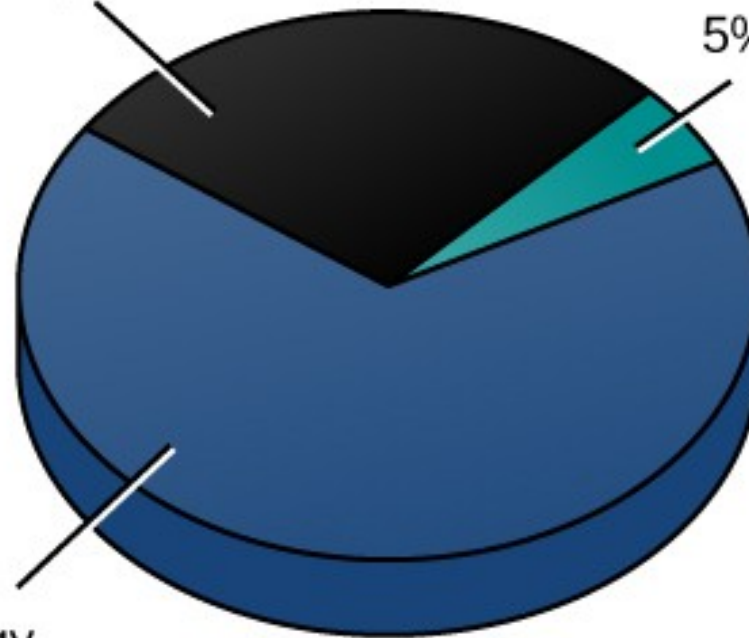
Dark energy  
68%



Dark matter  
27%

Ordinary matter  
5%

Dark energy  
68%



Ordinary matter  
4% H and He  
<1% Stars  
<1% Other



A dynamic, abstract background featuring a circular trail of glowing particles in shades of blue and cyan. The particles are concentrated in a ring, with some appearing as bright streaks and others as smaller, scattered dots. The overall effect is reminiscent of a particle detector or a cosmic event.

Thank you