Introduction to Particle Physics

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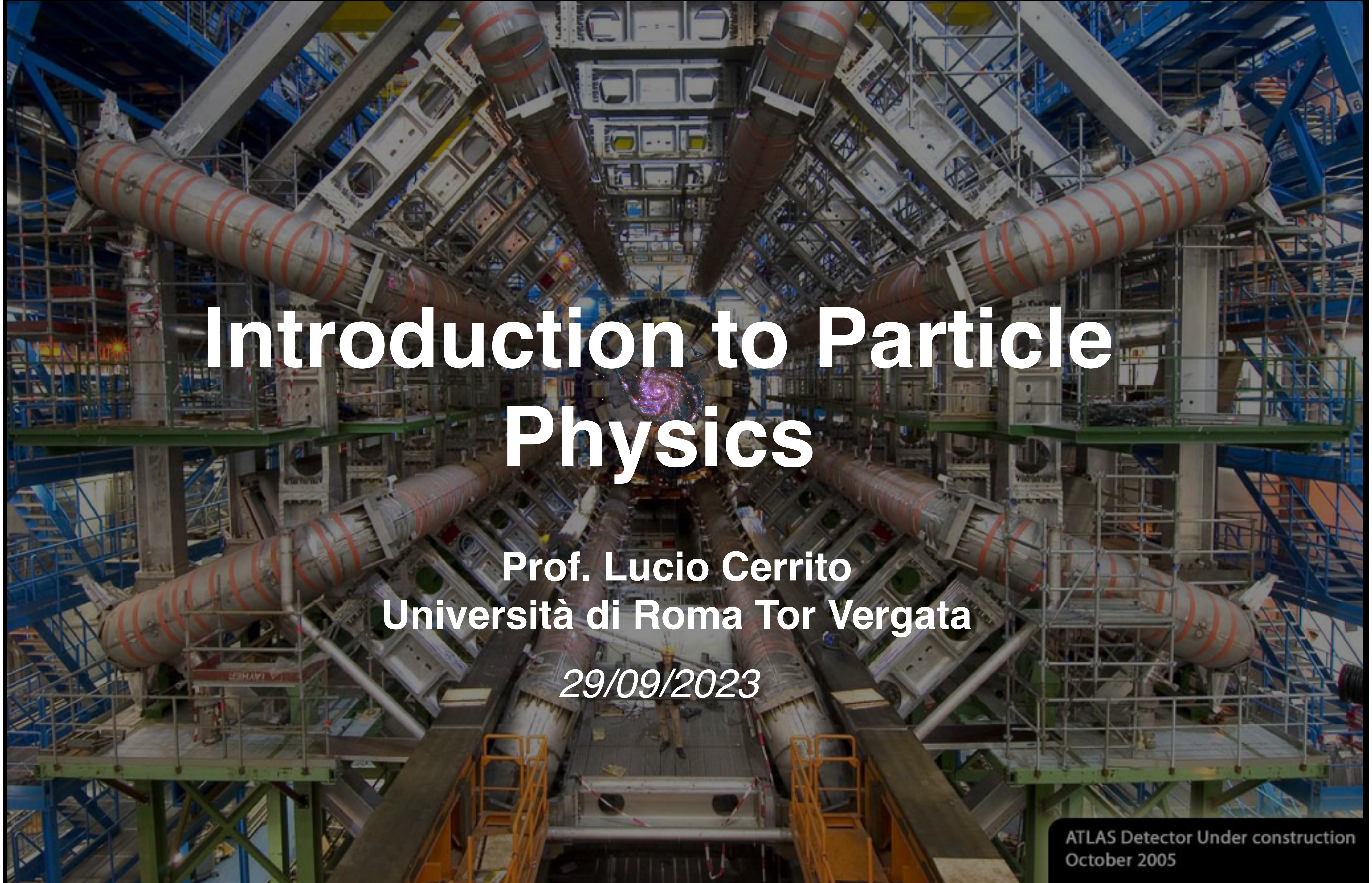
Università di Roma Tor Vergata

29/09/2023



ATLAS Detector Under construction
October 2005

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA
Dipartimento di Fisica

INFN Istituto Nazionale di Fisica Nucleare

INTERNATIONAL MASTERCLASSES
hands on particle physics

What is the subatomic
structure of our Universe ?

What are we really made of ?

What are the fundamental forces ?

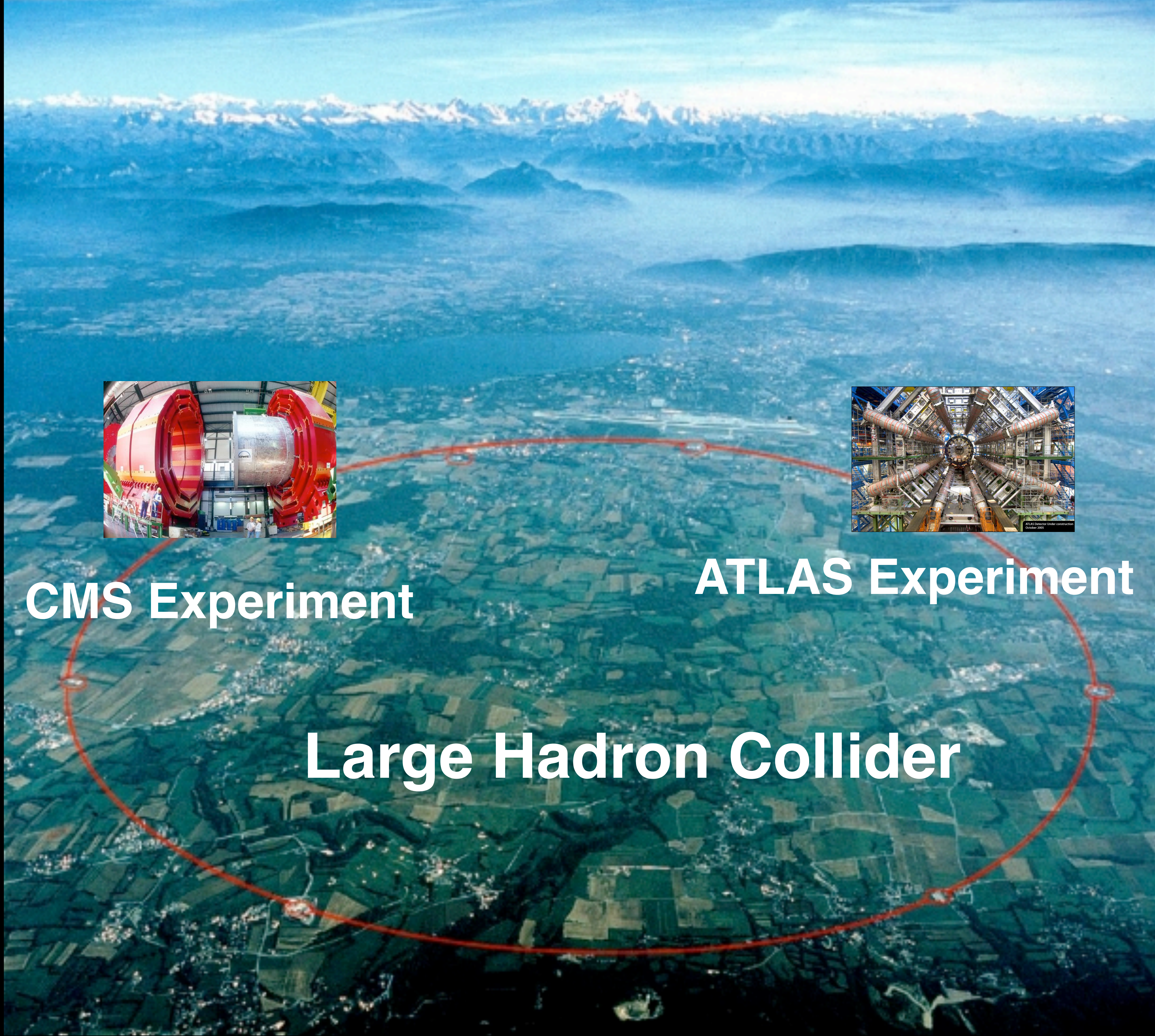
Can we even answer these questions ?

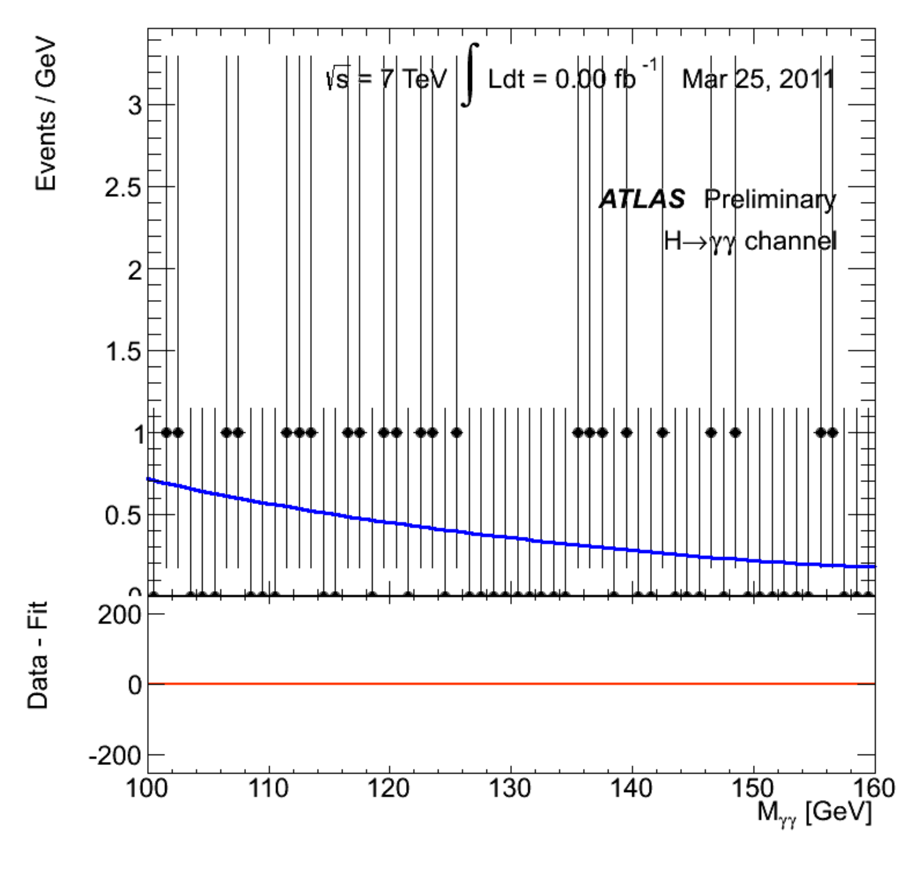
… and how ?

July 4th, 2012

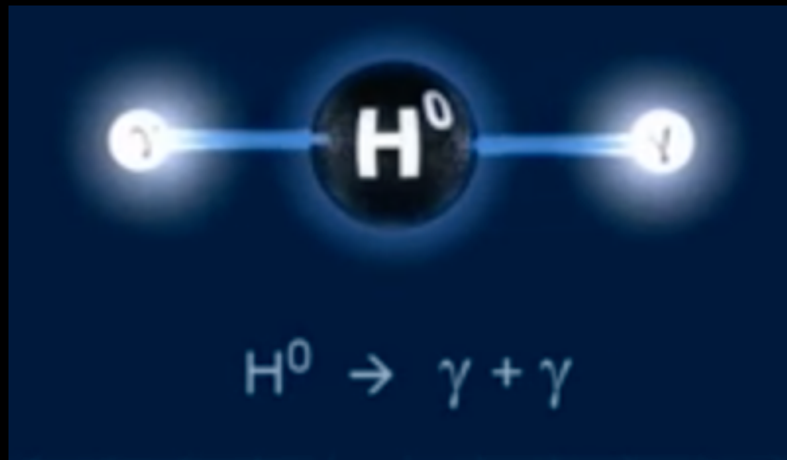
European Organization for Nuclear Research

Franco-Swiss border, near Geneva


CMS Experiment
ATLAS Experiment
Large Hadron Collider



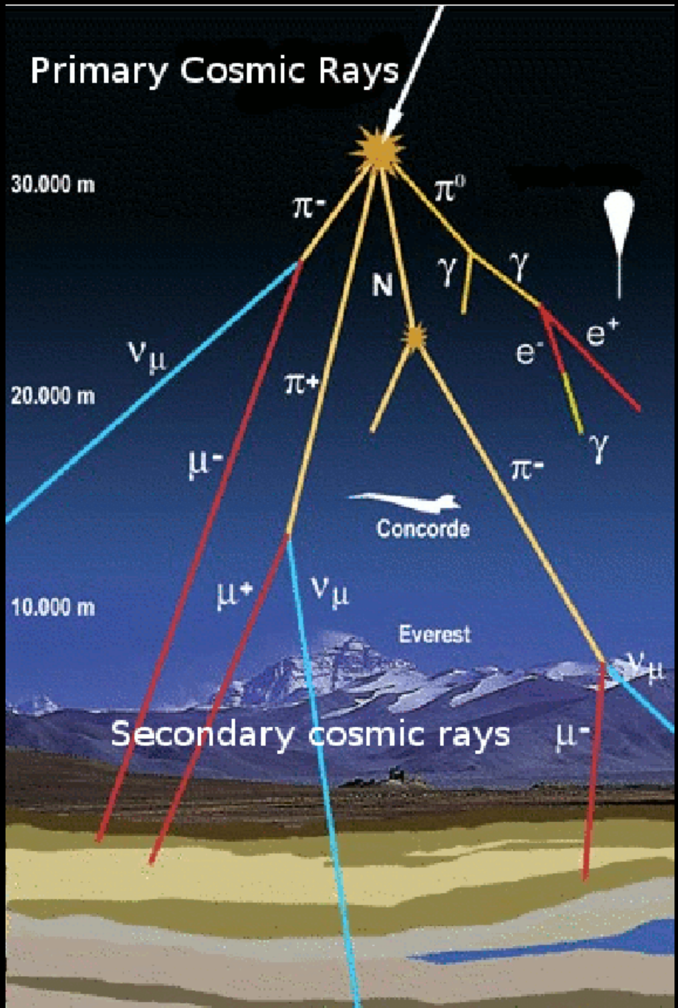
Discovery of the Higgs Boson

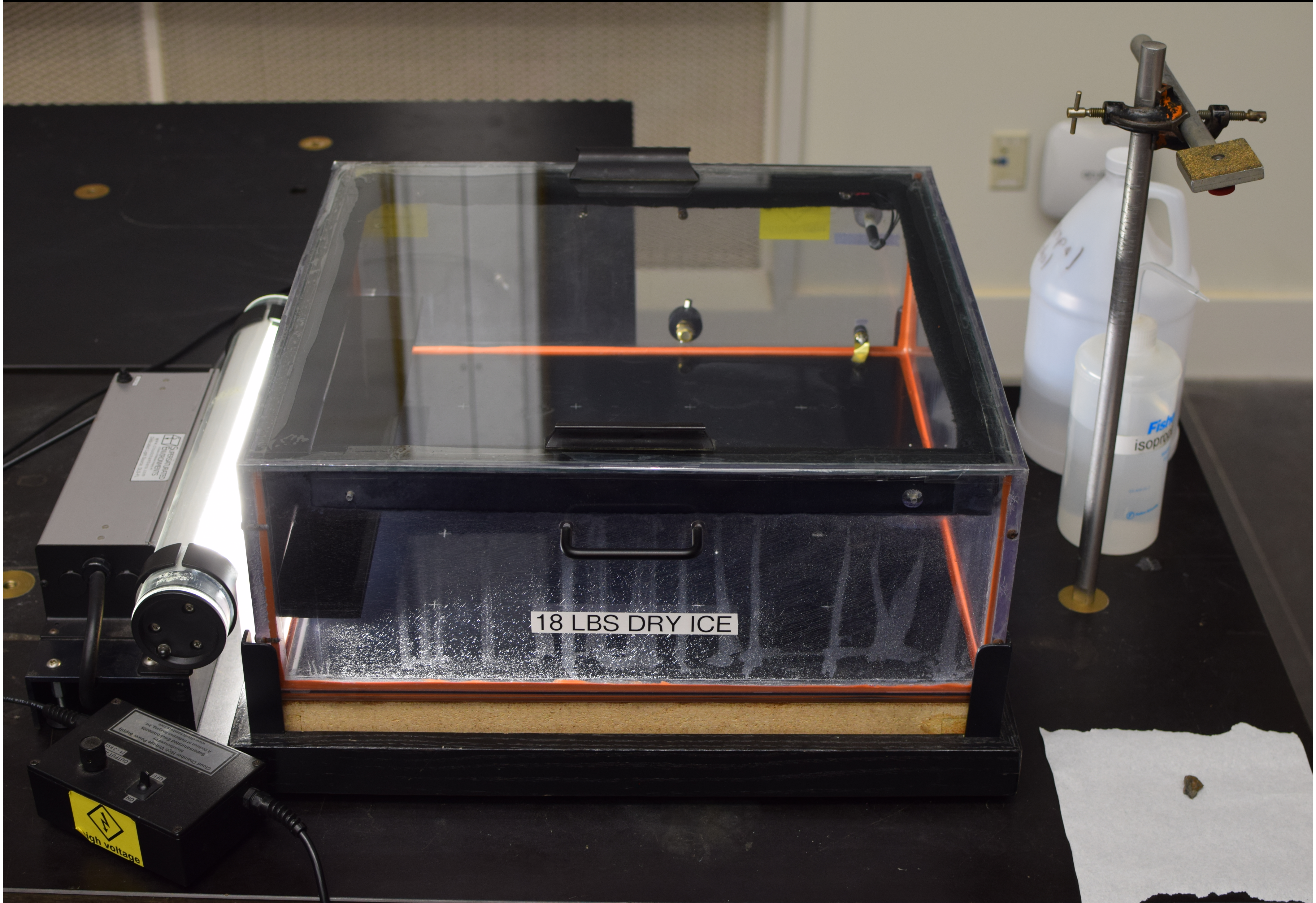


Existence of a Higgs field showing ripples

Nobel Prize, 2013

The Complex Subatomic World


Primary Cosmic Rays
30.000 m
20.000 m
10.000 m
π-
π0
N
γ
γ
e+
e-
γ
νμ
π+
μ-
π-
Concorde
μ+
νμ
Everest
νμ
Secondary cosmic rays
μ-


18 LBS DRY ICE

Structure of the Atom

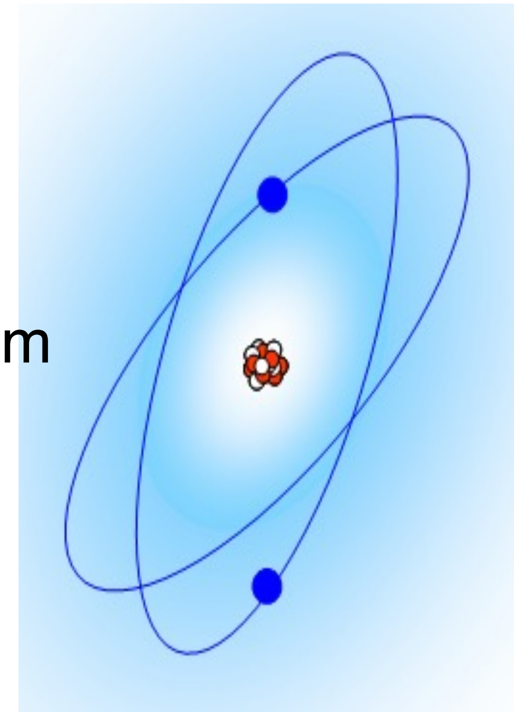
Electron already discovered in 1897 by J. J. Thomson

1930s

Simple picture
3 elementary particles

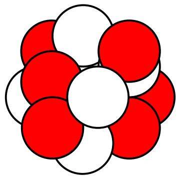
1911 nucleus, electron
electromagnetism
long range $1 / r^2$

Atom $\sim 10^{-10}$ m



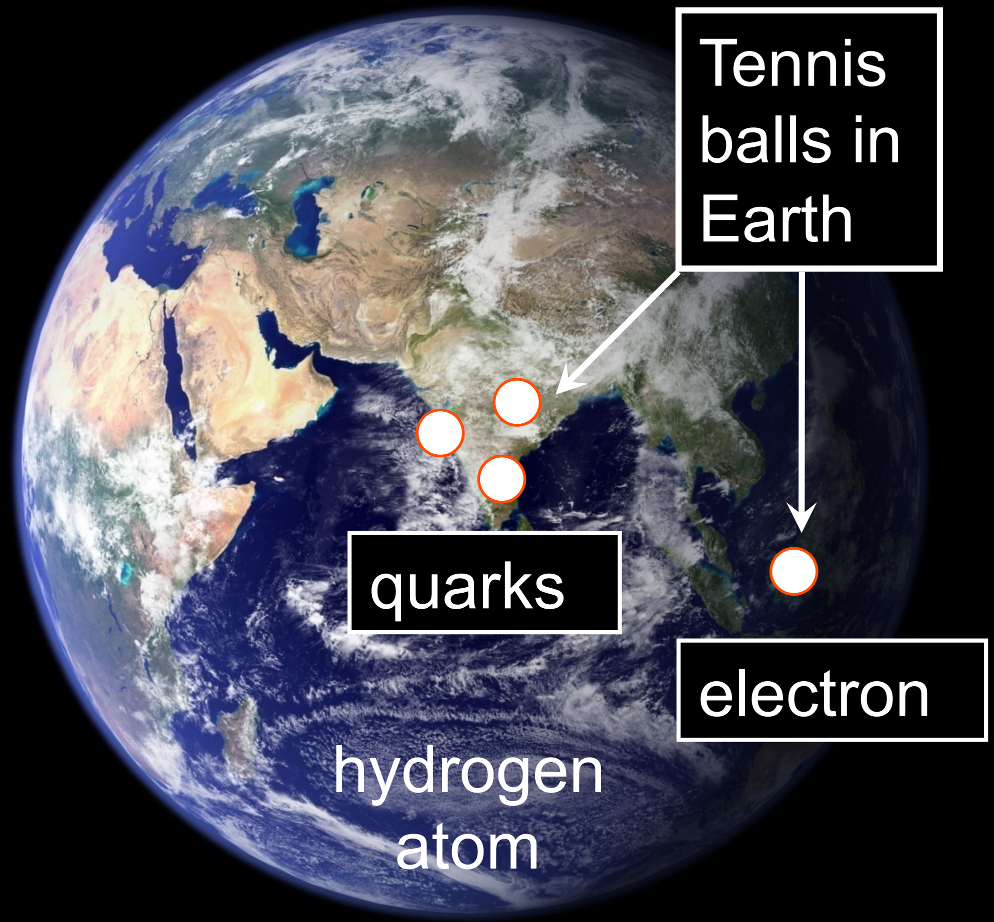
1932 neutron discovered by James Chadwick

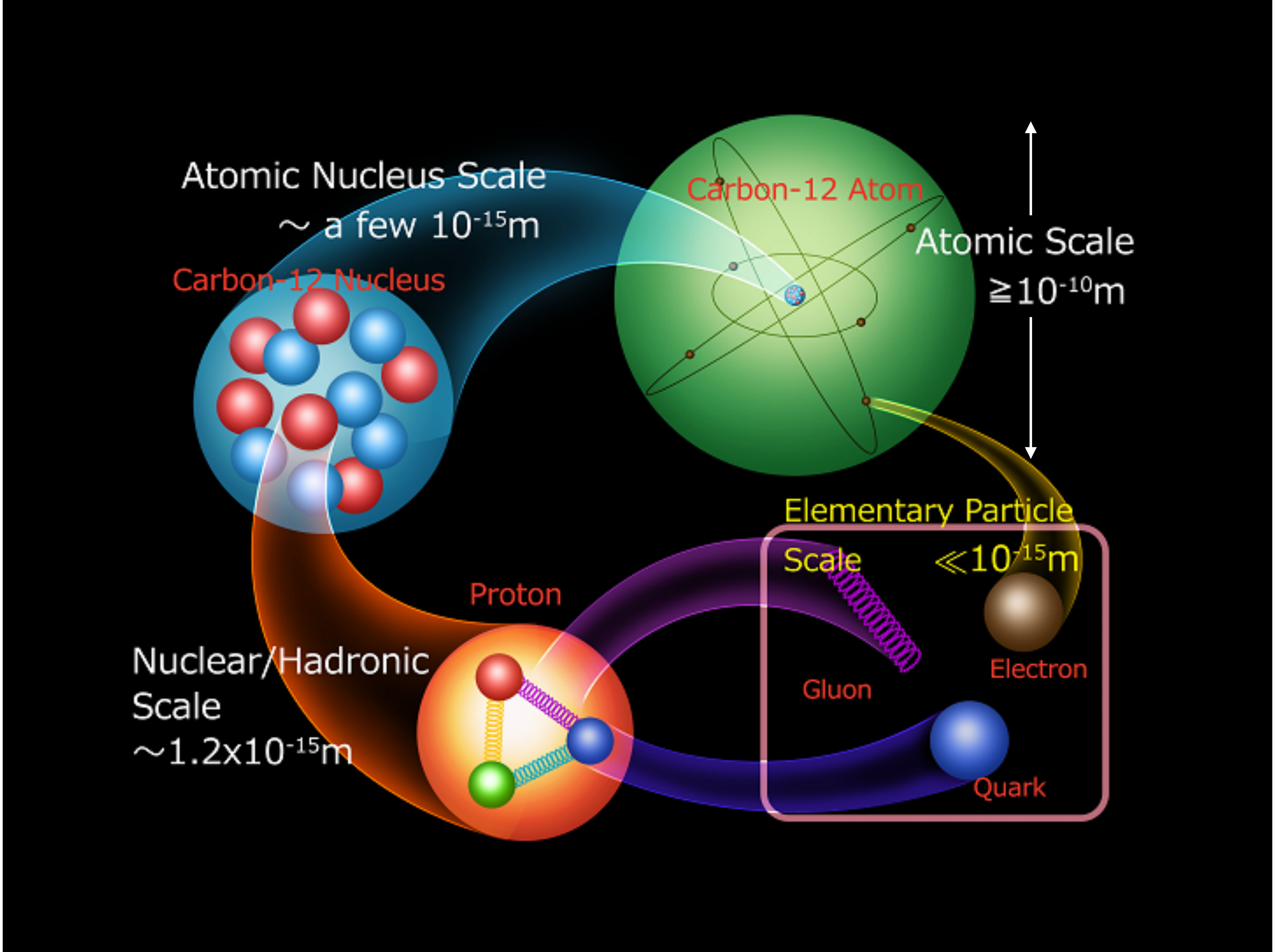
Nucleus

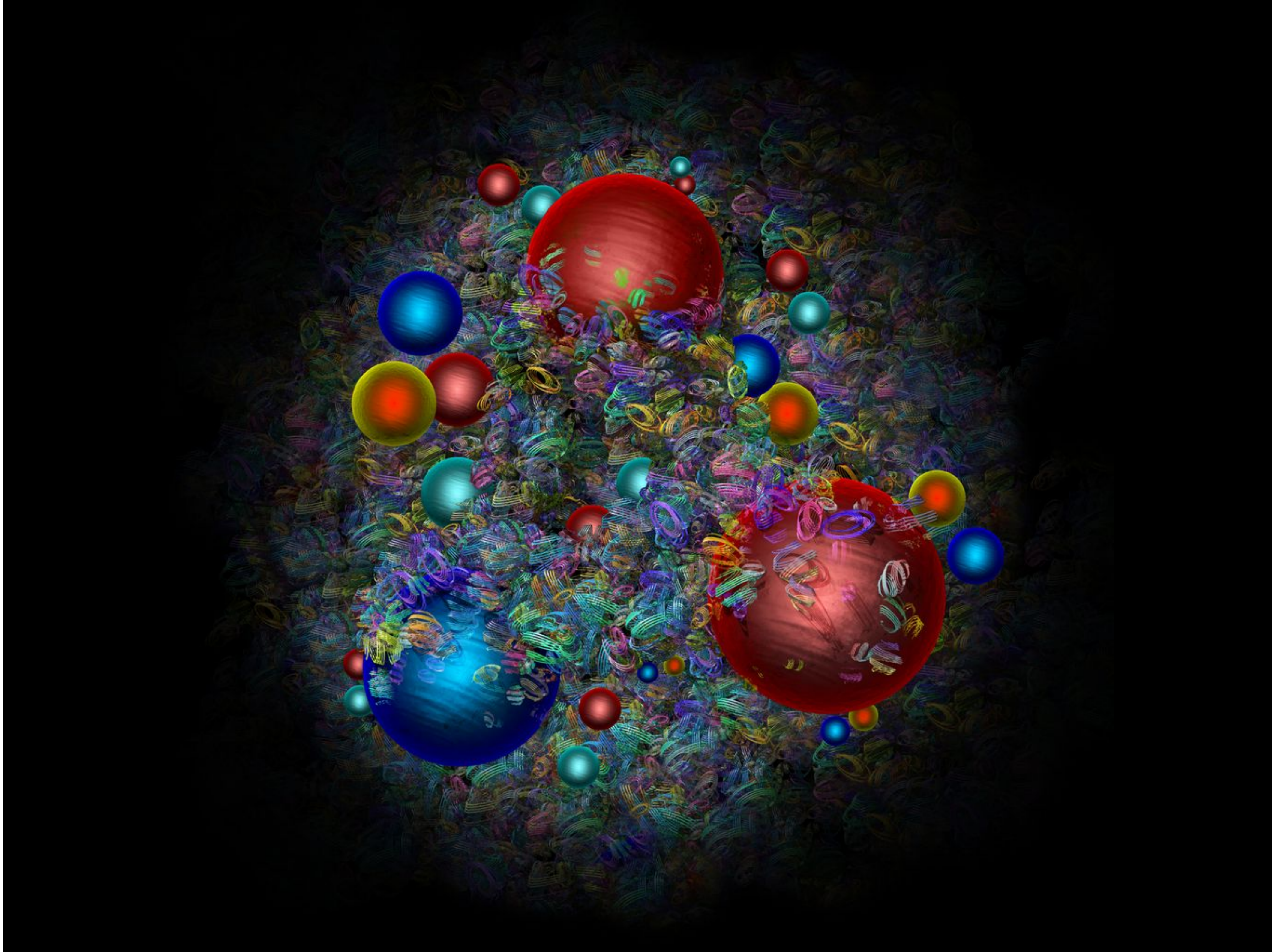


$\sim 10^{-15}$ m

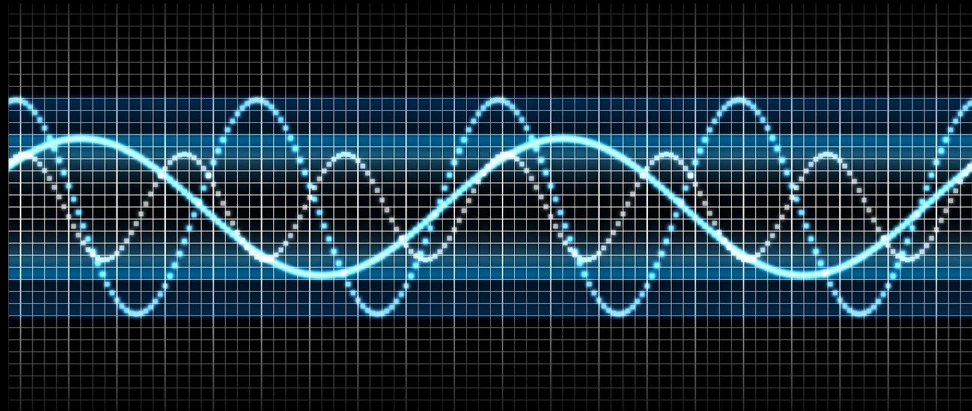
Proton + ●
Neutron ○
strong force
short range


Tennis balls in Earth
quarks
electron
hydrogen atom

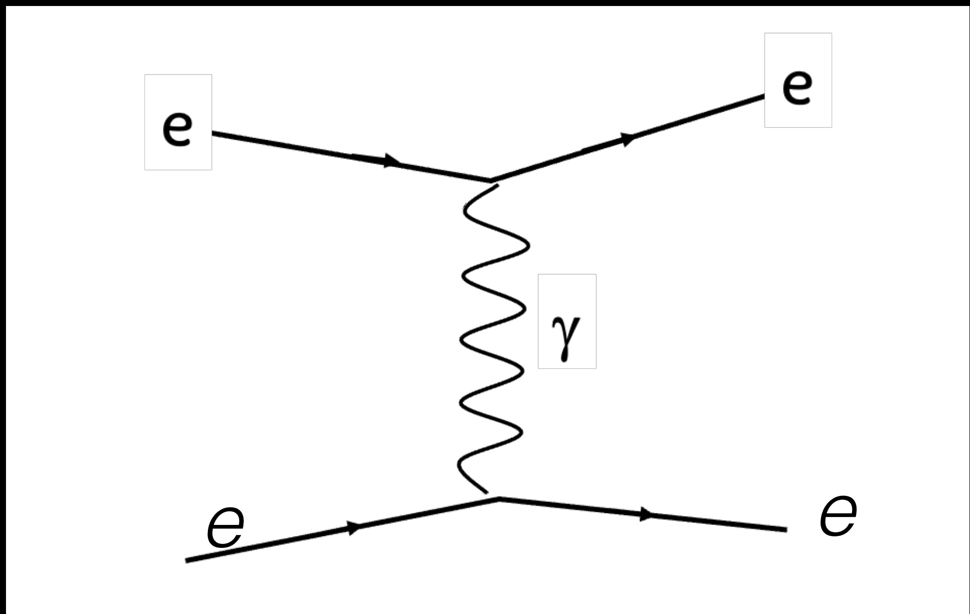

Atomic Nucleus Scale
～ a few 10-15m
Carbon-12 Nucleus
Carbon-12 Atom
Atomic Scale
≧10-10m
Elementary Particle
Scale ≪10-15m
Proton
Nuclear/Hadronic
Scale
～1.2x10-15m
Gluon
Electron
Quark



Special Relativity



Quantum Mechanics



Feynman Diagram

Constituents

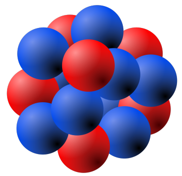
How can we find internal structure?

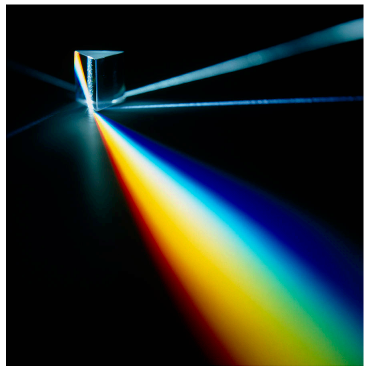
Insect

1 lens : Magnifying glass
2 lenses : Microscope
3 lenses : No improvement

Resolution limited by wavelength of light = λ

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 λ
lower by factor more than a billion !

Quantum physics to the rescue

Particles have wave properties

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

h ← Planck constant

p ← momentum

"See" small objects

→ small wavelength

→ high momentum

→ high energy

→ large accelerator

To observe the smallest objects we need the largest machines !

Non-relativistic

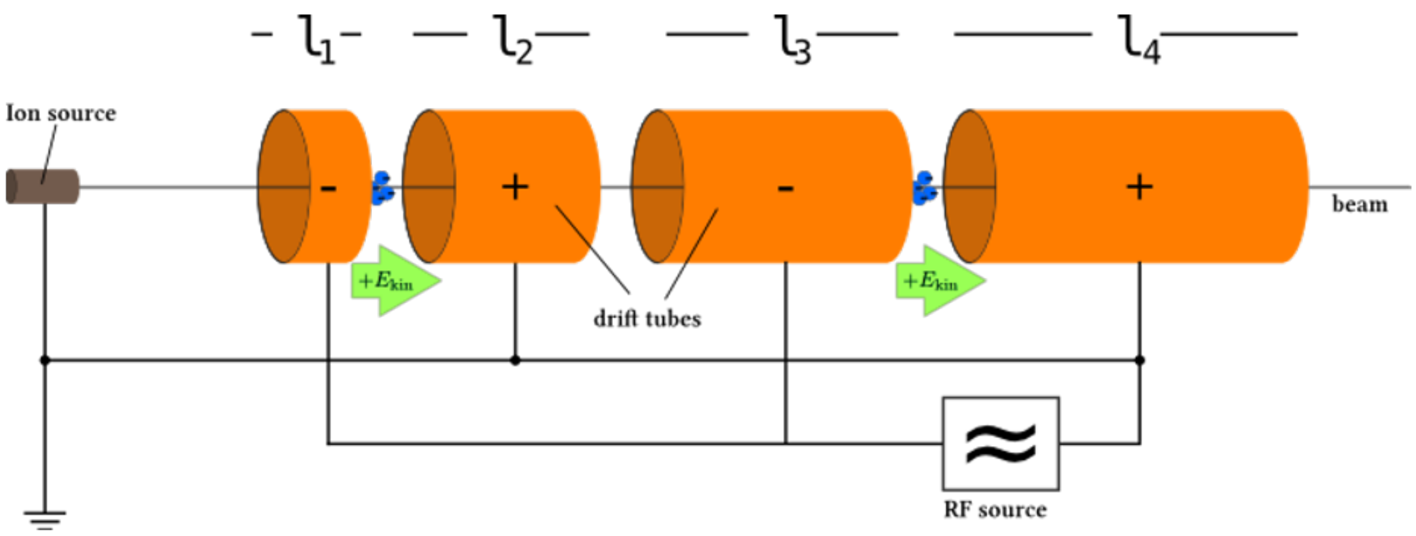
$p = m\,v$

mass x velocity

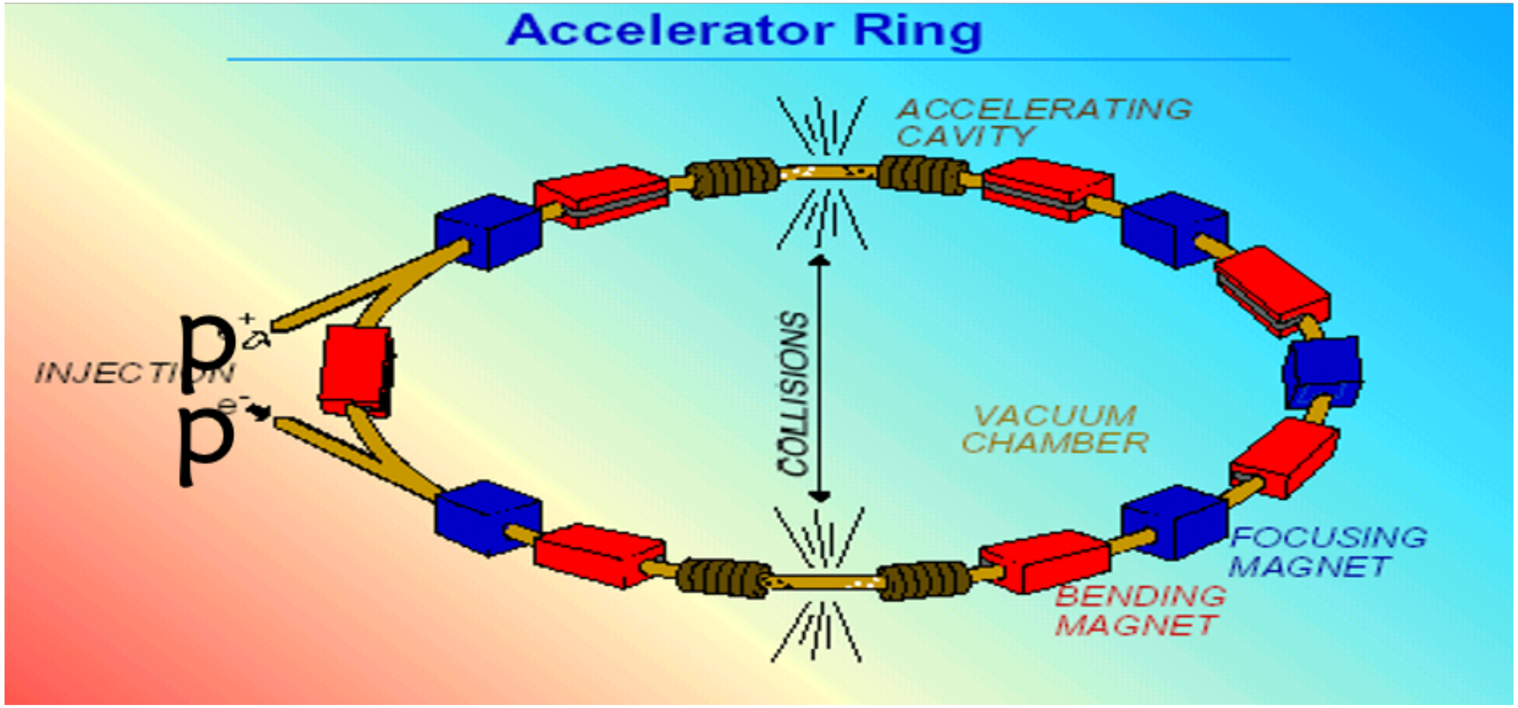
Relativistic

$p = \gamma\, m\, v$

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



Linear



Circular

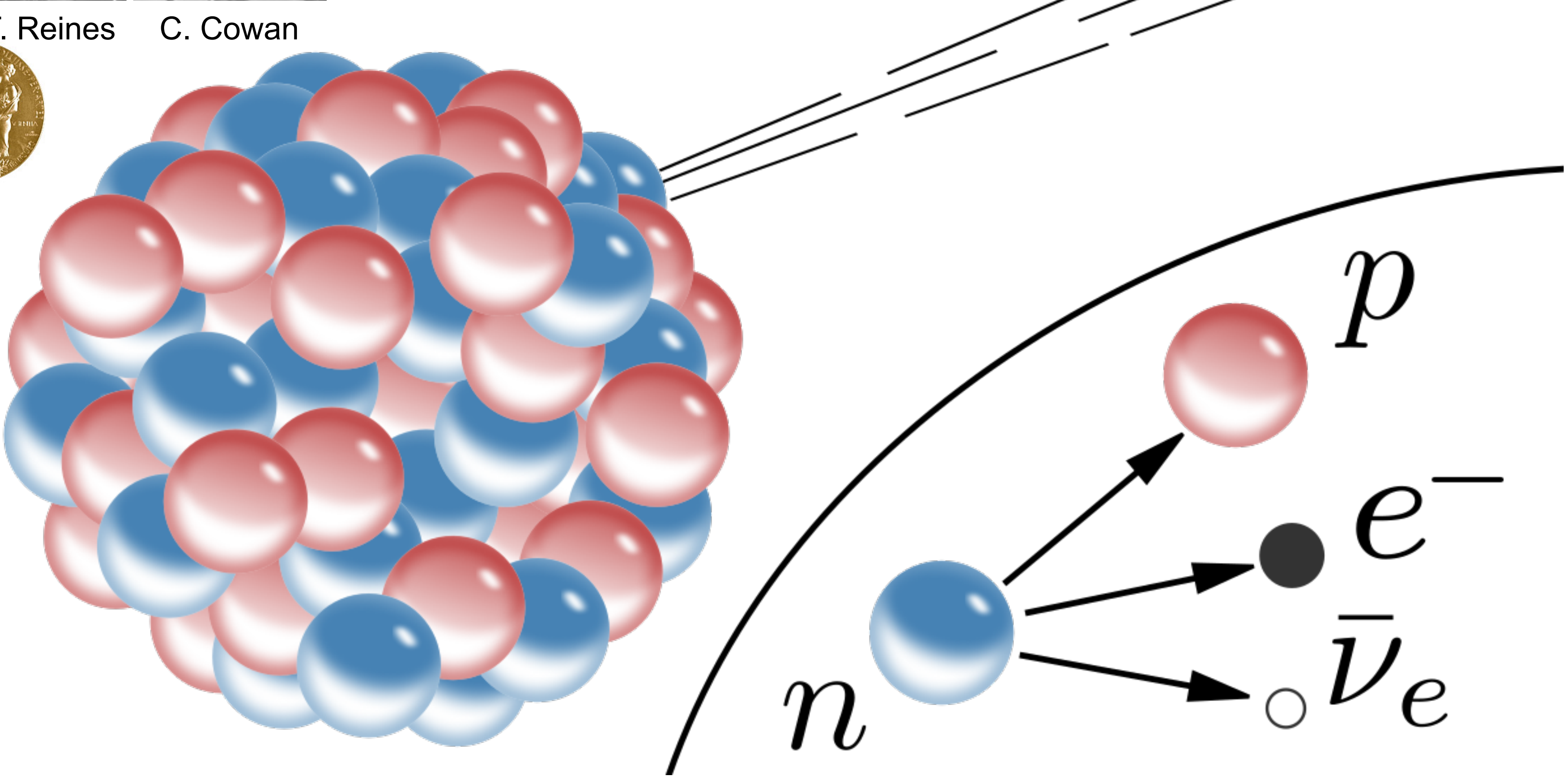
Neutrinos

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

W.Pauli

F. Reines

C. Cowan

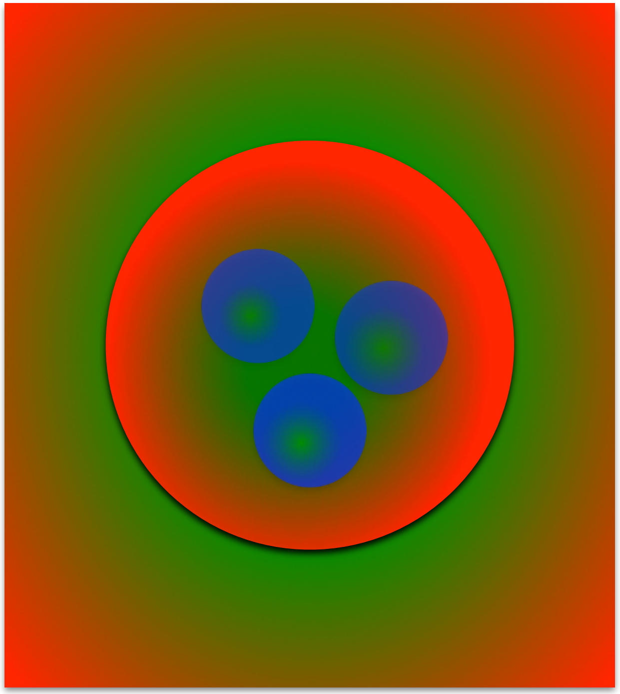


Leptons

electron e^- -1	do not feel strong force
neutrino ν_e 0	

Quarks

up u +2/3	feel strong force
down d -1/3	



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 μ^- -1	tau τ^- -1
	neutrino ν_e 0	neutrino ν_μ 0	neutrino ν_τ 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

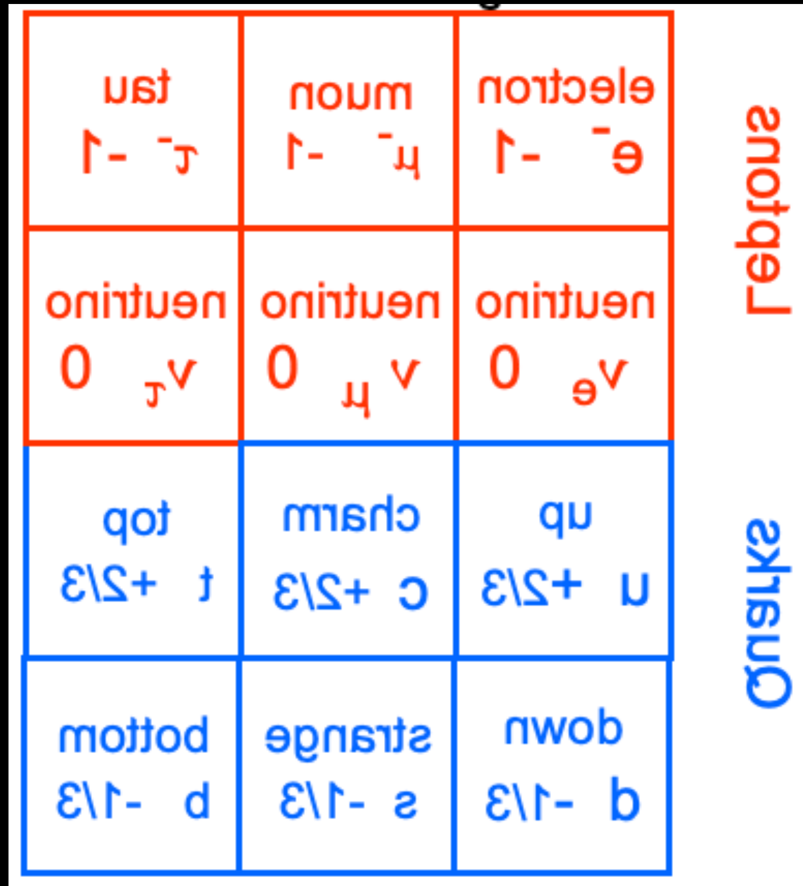
3 generations

x 2 for antiparticles

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

Leptons	electron e^- -1	muon μ^- -1	tau τ^- -1
	neutrino ν_e 0	neutrino ν_μ 0	neutrino ν_τ 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

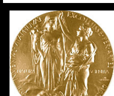


ANTI-MATTER

Antiparticles

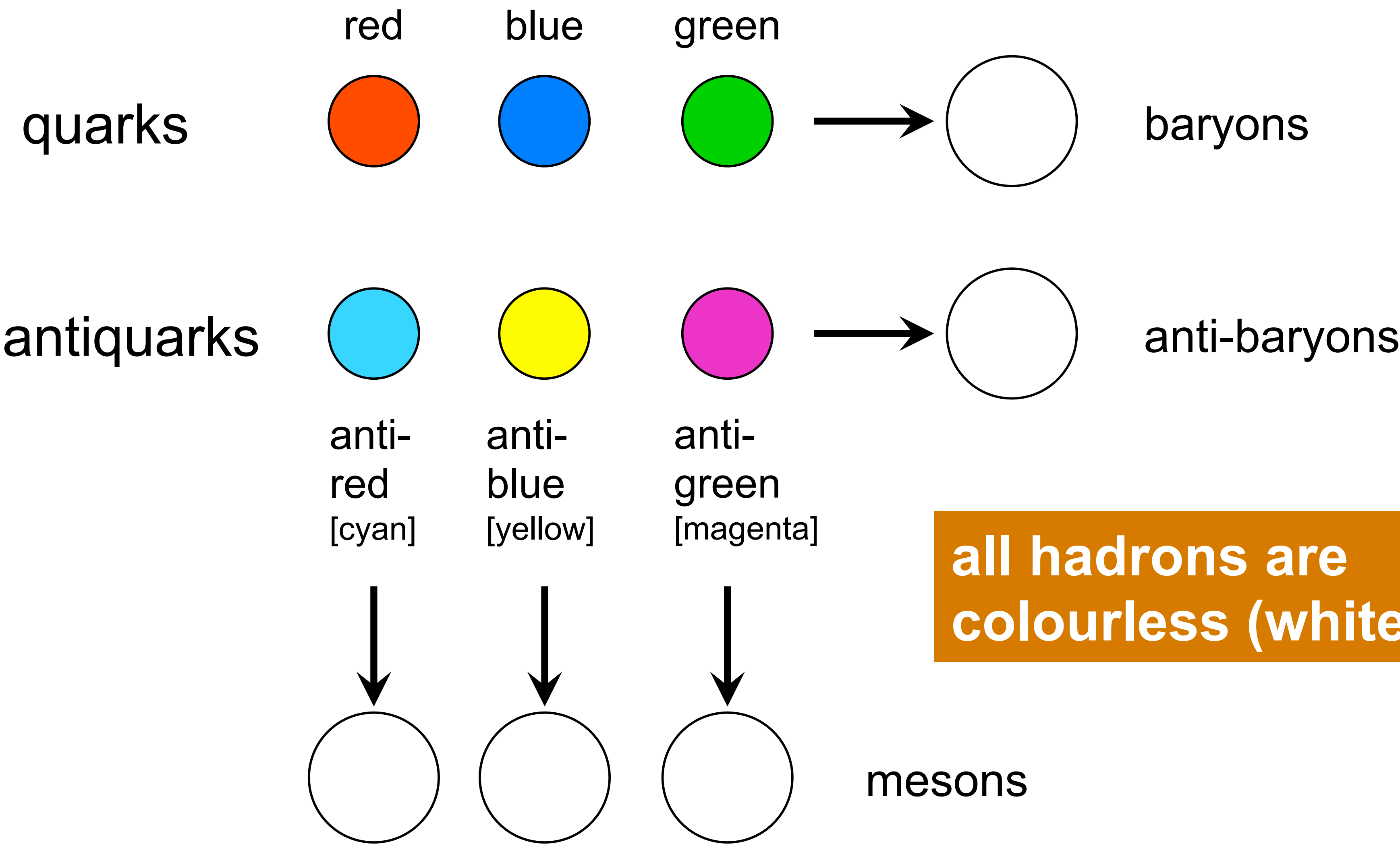
P.Dirac

C. Anderson

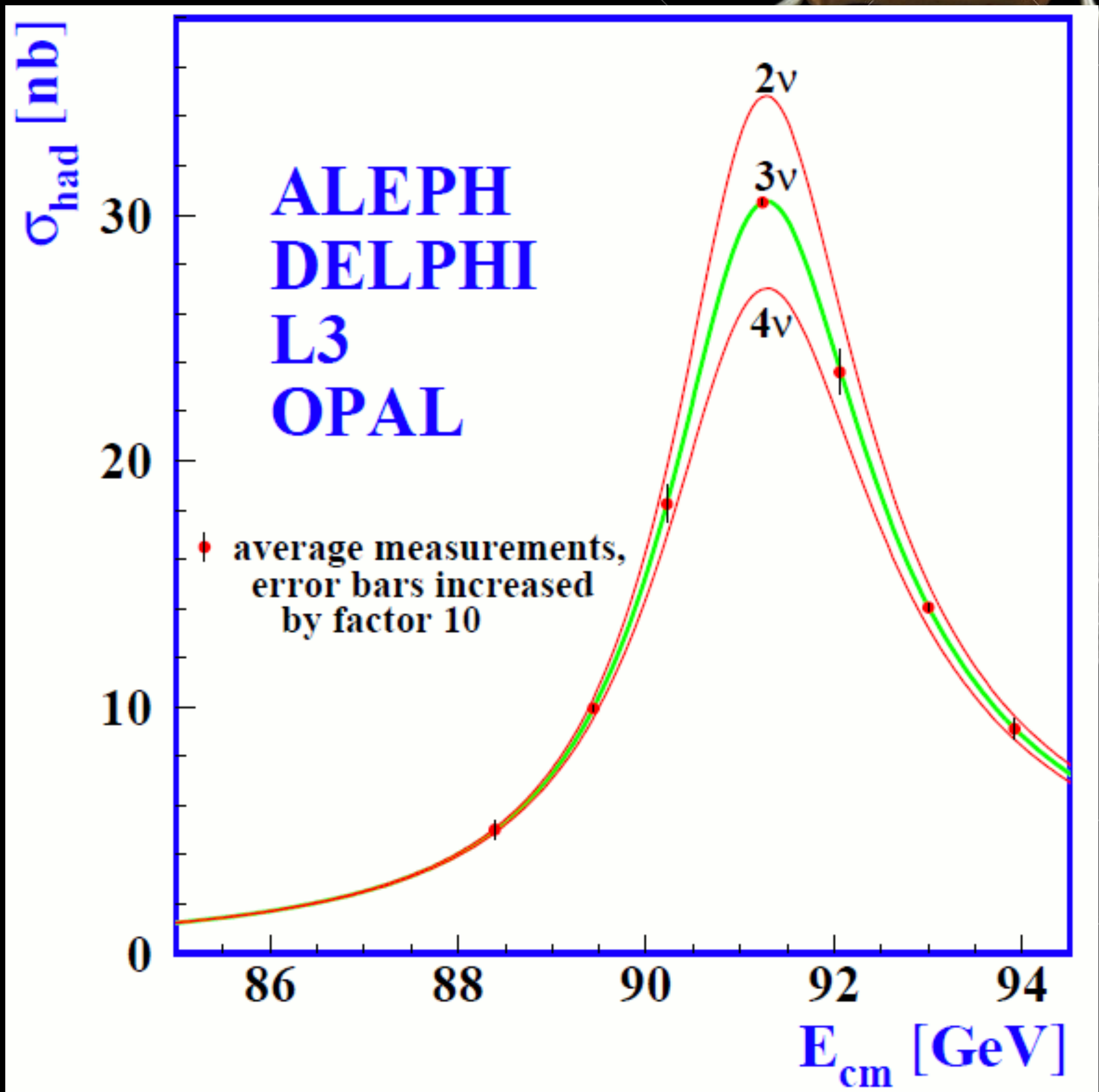


Equal and opposite properties
"predicted" → later discovered
Annihilate with normal particles
Now used in PET scans

Colour: Strong force “equivalent” of charge



all hadrons are colourless (white)



Uncertainty Principle

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

Z line shape

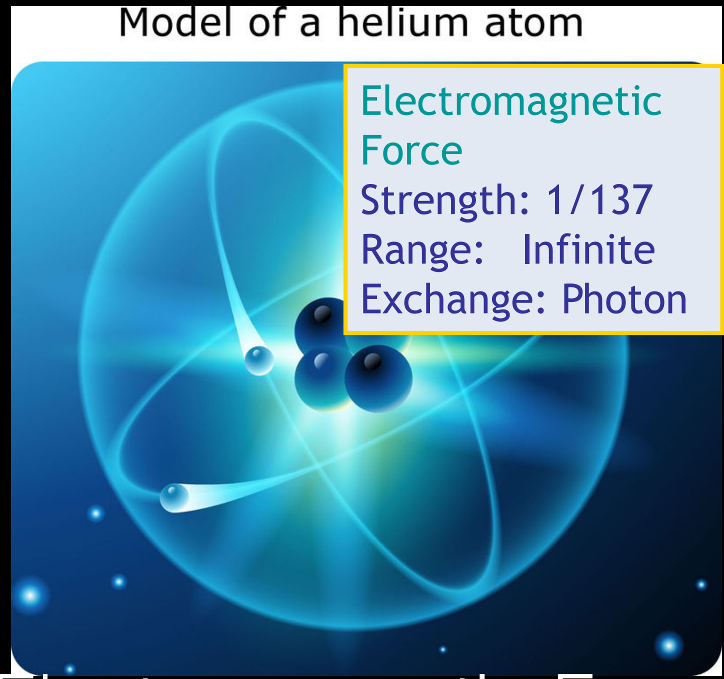
$N_{\nu} = 2.994 \pm 0.011$

Discovery of top quark
Pattern completed March 2nd, 1995

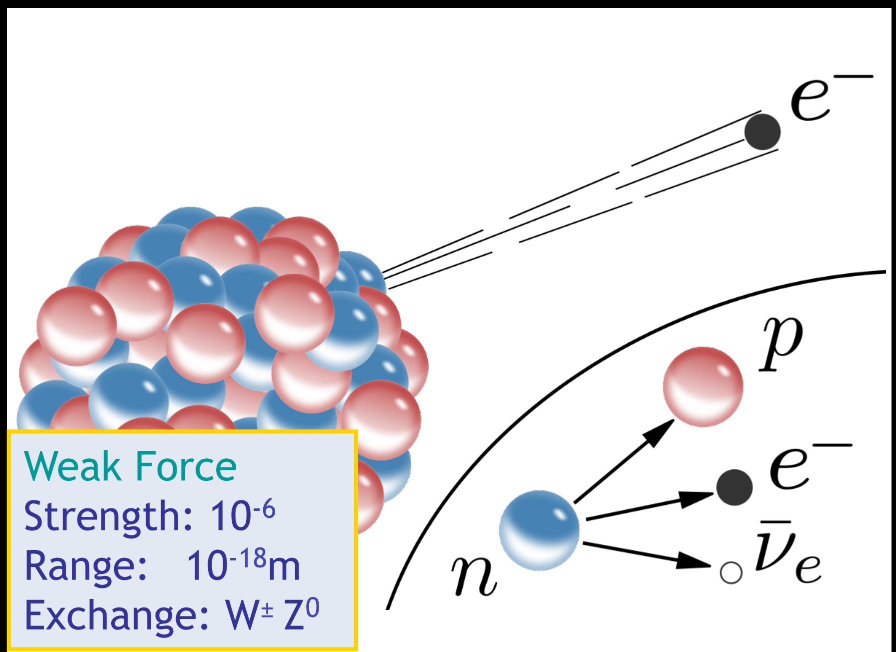
U.S. Fermi National Accelerator Laboratory

Illinois - Chicago

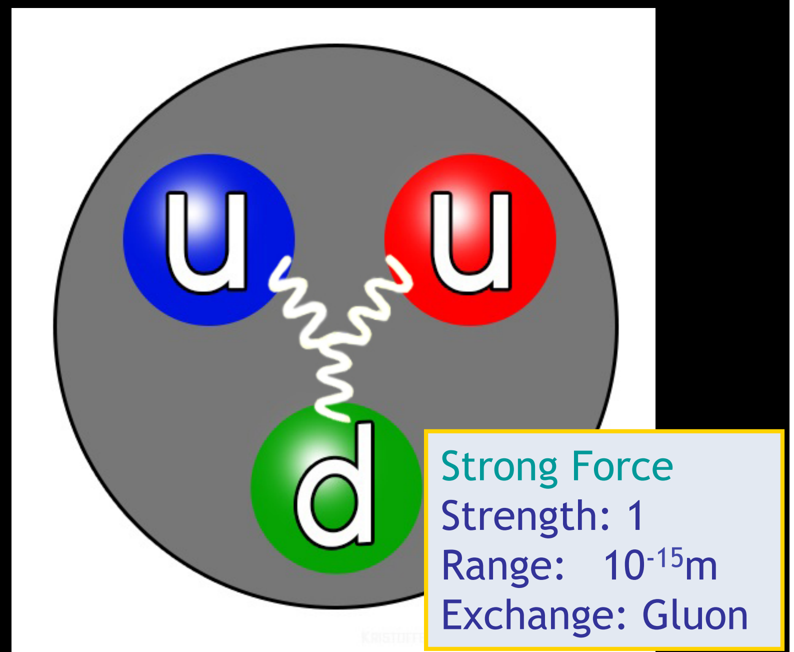
Gravitational Force



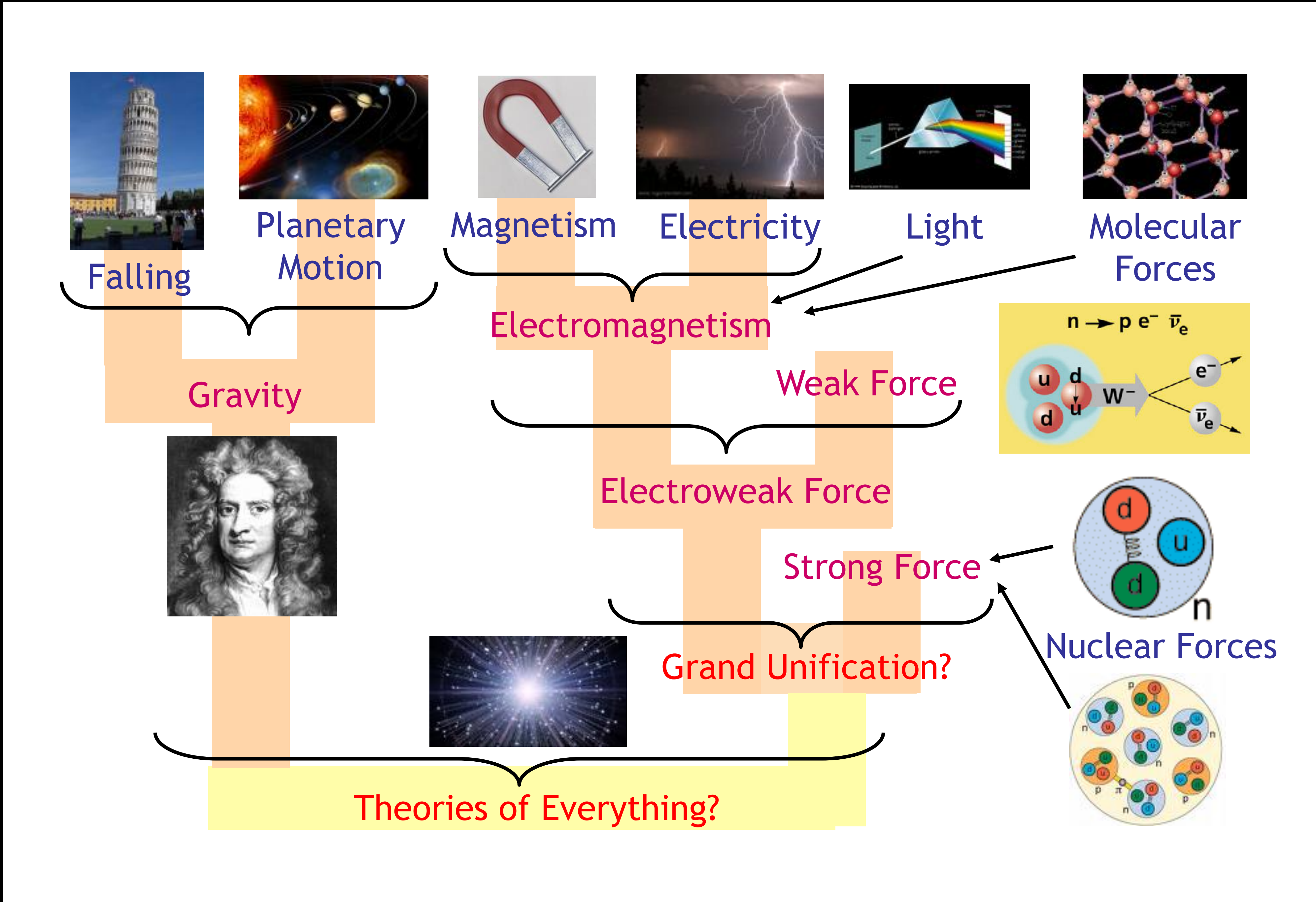
Electromagnetic Force

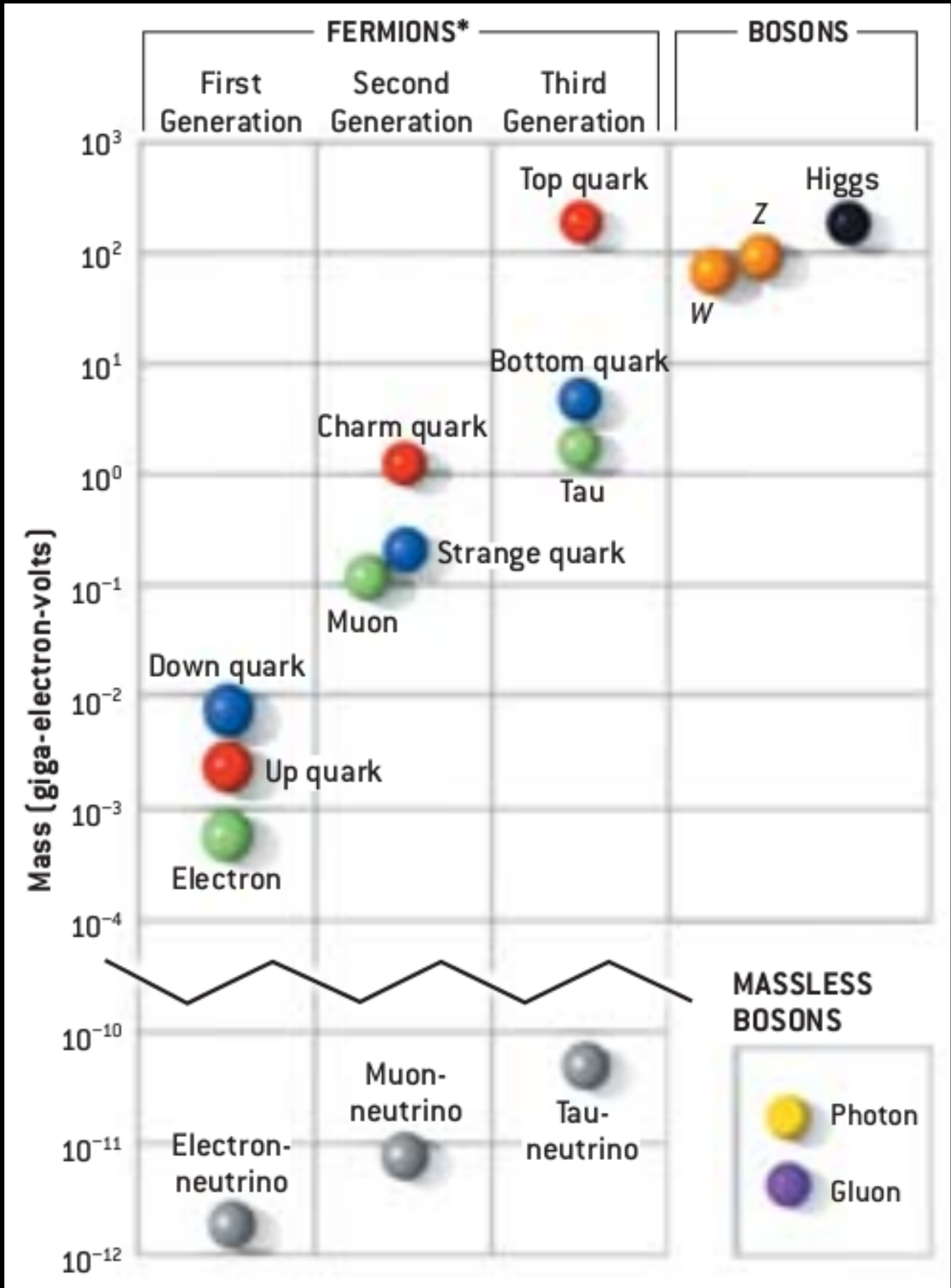


Weak Nuclear Force



Strong Nuclear Force

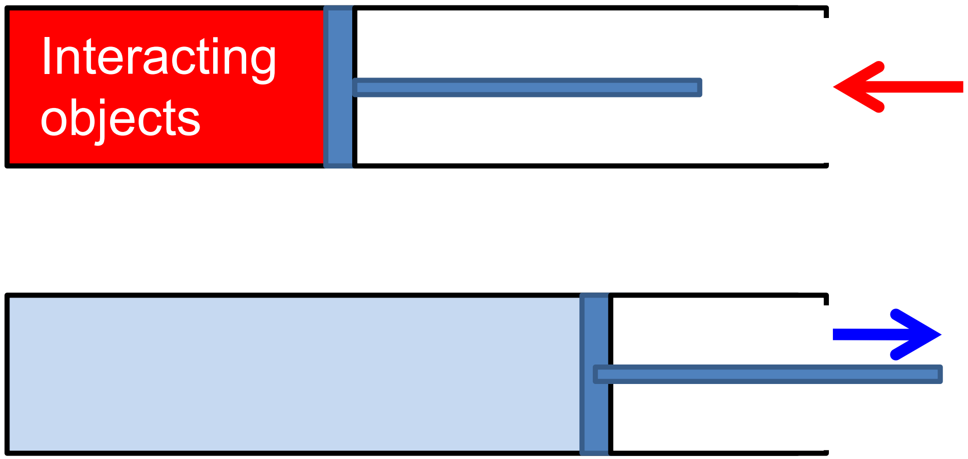

Falling
Planetary Motion
Magnetism
Electricity
Light
Molecular Forces
Gravity
Electromagnetism
Weak Force
n → p e⁻ ν̄e
u
d
d
u
W⁻
e⁻
ν̄e
Electroweak Force
Strong Force
d
u
d
n
Nuclear Forces
Grand Unification?
Theories of Everything?



We don't understand why such value of masses …

A Window to the Early Universe

Analogy



Compress : Heat
more dense

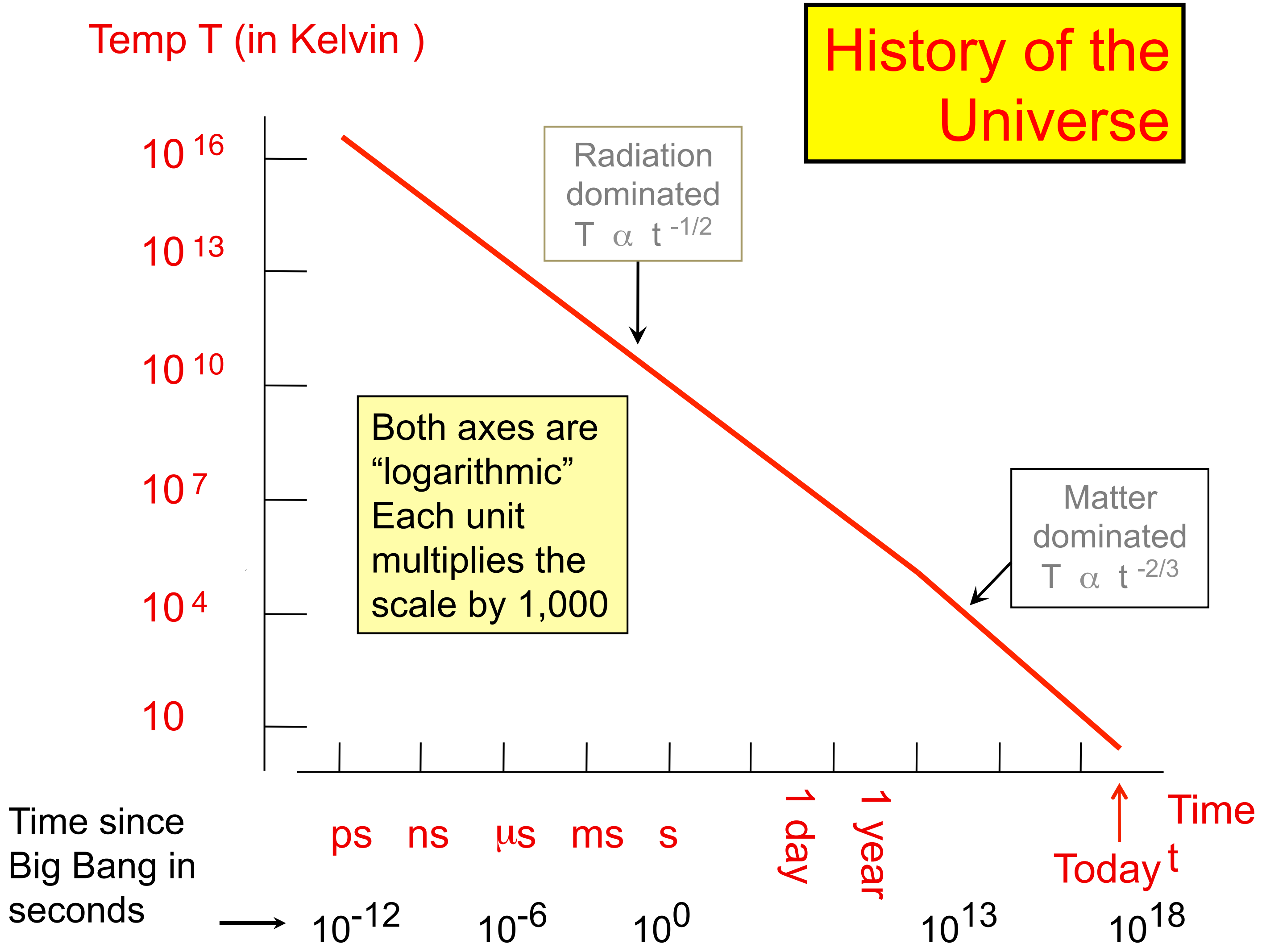
Expand : Cool
less dense

Universe is expanding → Cooling

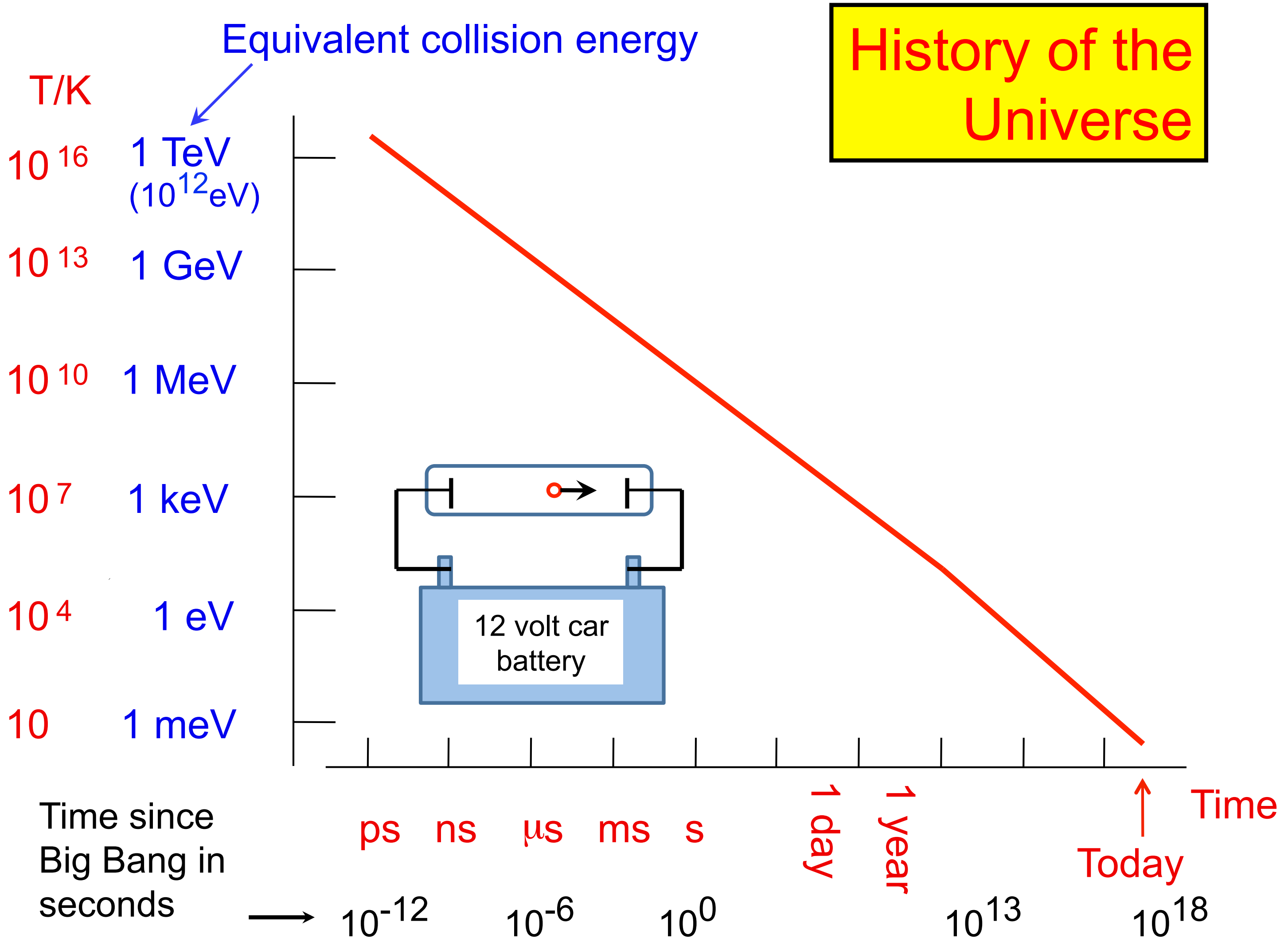
In the past → Universe was hotter

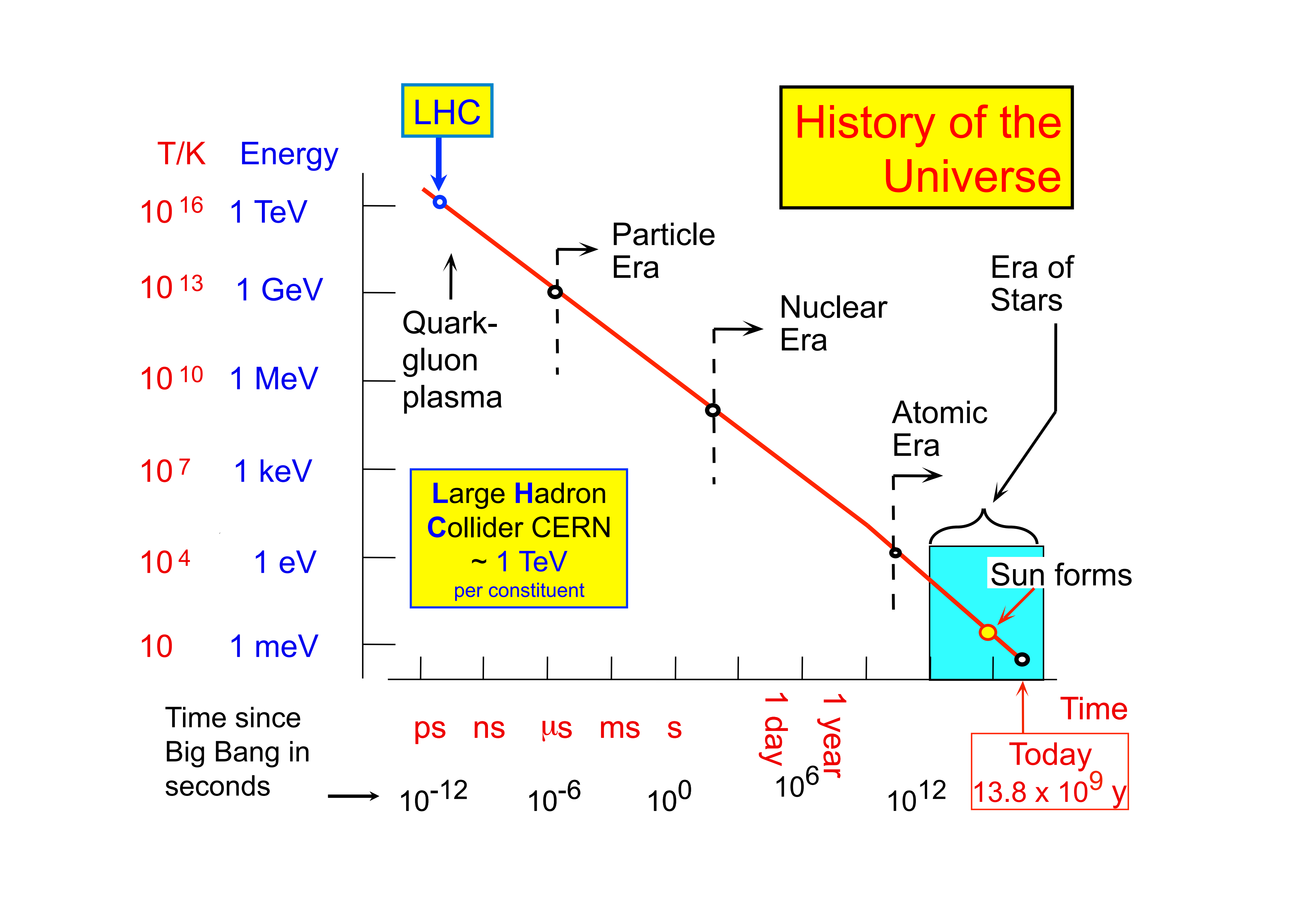
Hot Big Bang Model

History of the Universe

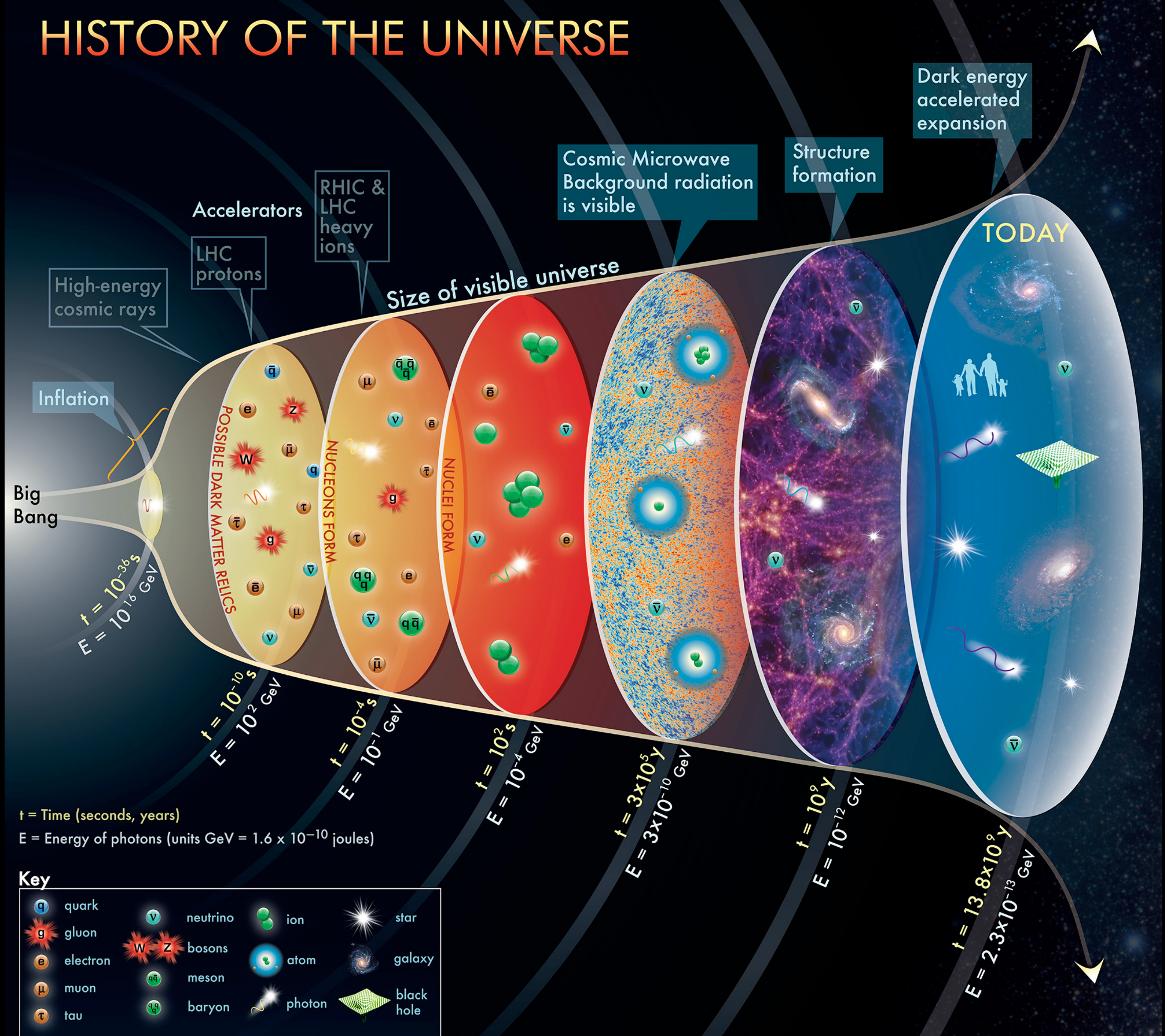


History of the Universe



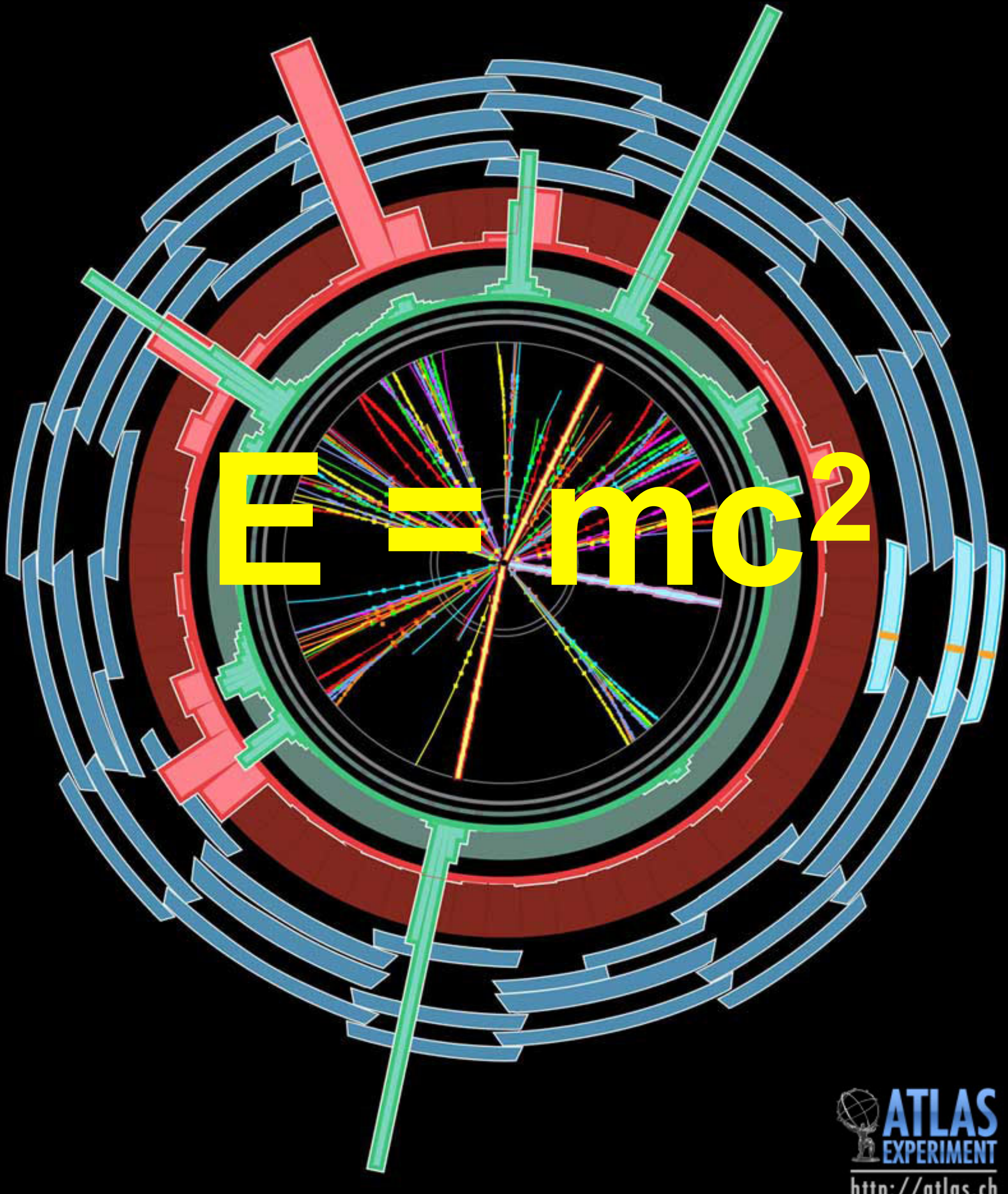


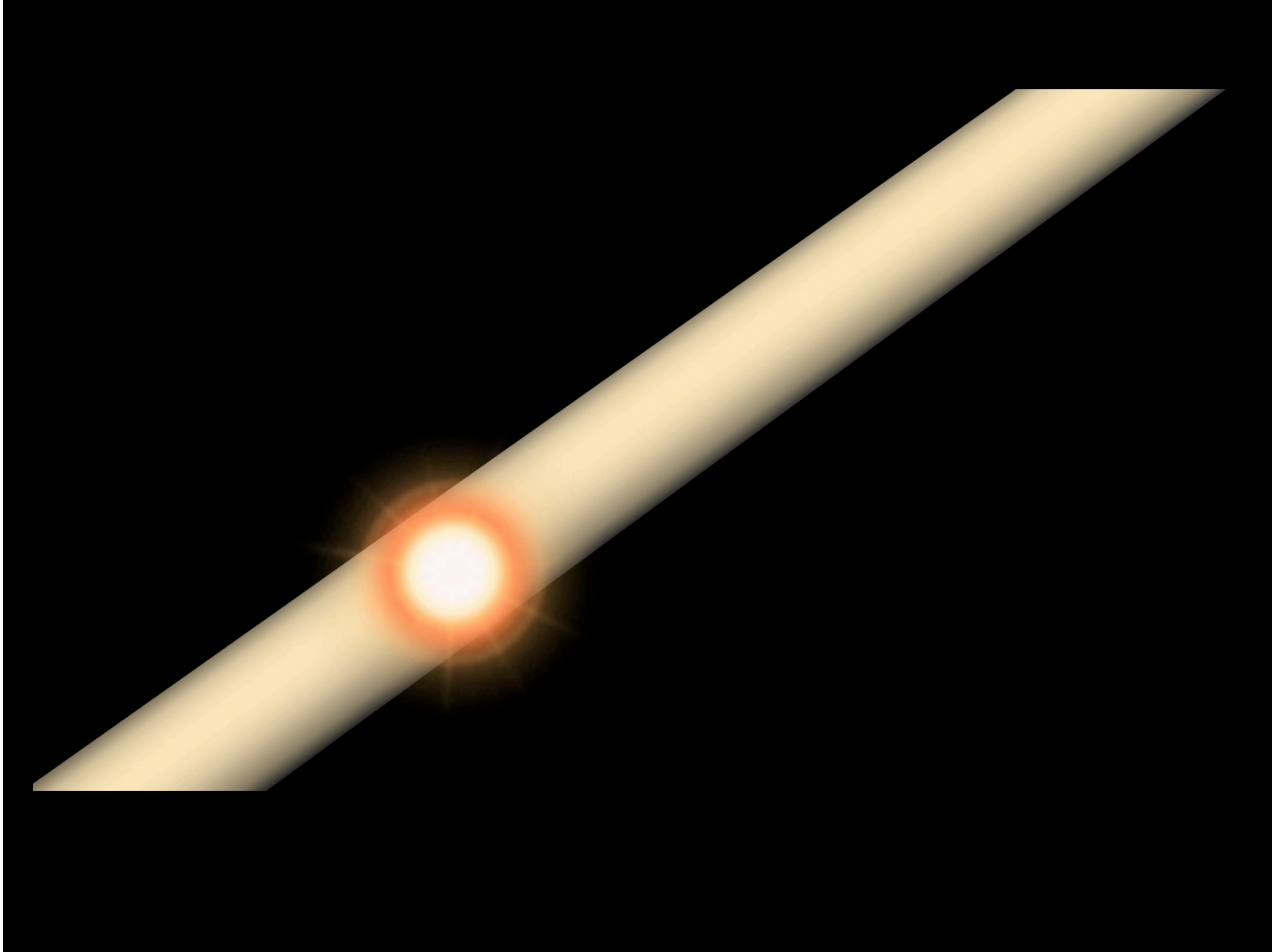
History of the Universe
LHC
T/K
Energy
10 16
1 TeV
10 13
1 GeV
10 10
1 MeV
10 7
1 keV
10 4
1 eV
10
1 meV
Quark-gluon plasma
Particle Era
Nuclear Era
Atomic Era
Era of Stars
Sun forms
Large Hadron Collider CERN
~ 1 TeV
per constituent
ps
ns
μs
ms
s
1 day
1 year
Time
Time since Big Bang in seconds
10-12
10-6
100
106
1012
Today
13.8 x 109 y


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

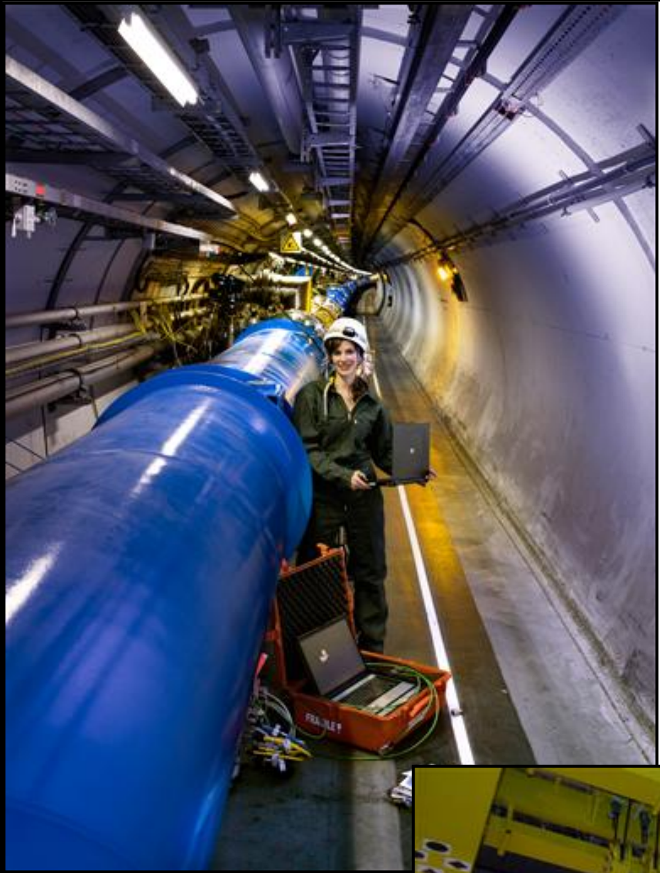
A Machine Powerful Enough

$$E = mc^2$$





Building the LHC



Superconducting Magnets

Superfluid Helium (Quantum liquid)

8.36 Tesla, 100,000 times the Earth's magnetic field

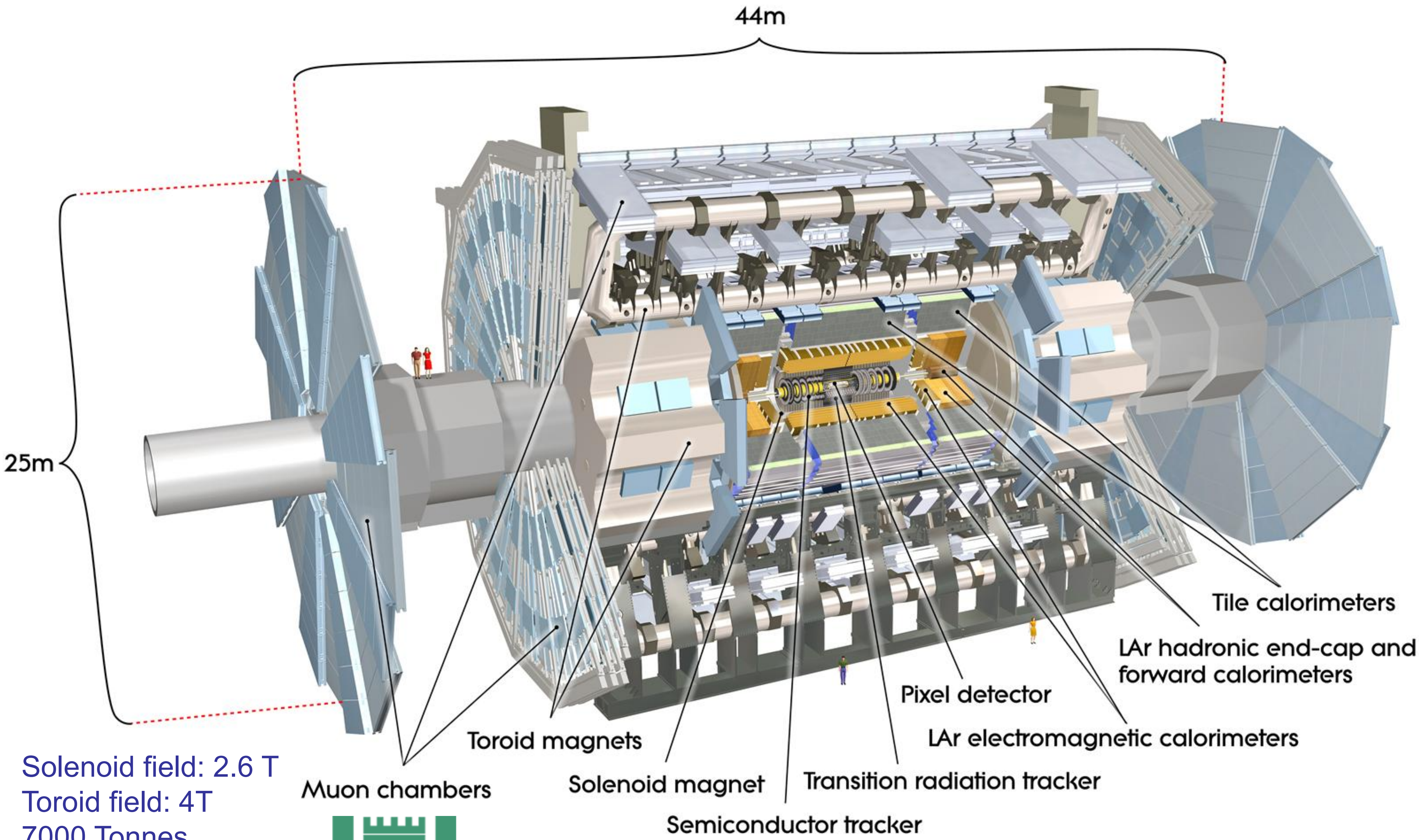
>1200 dipole magnets

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

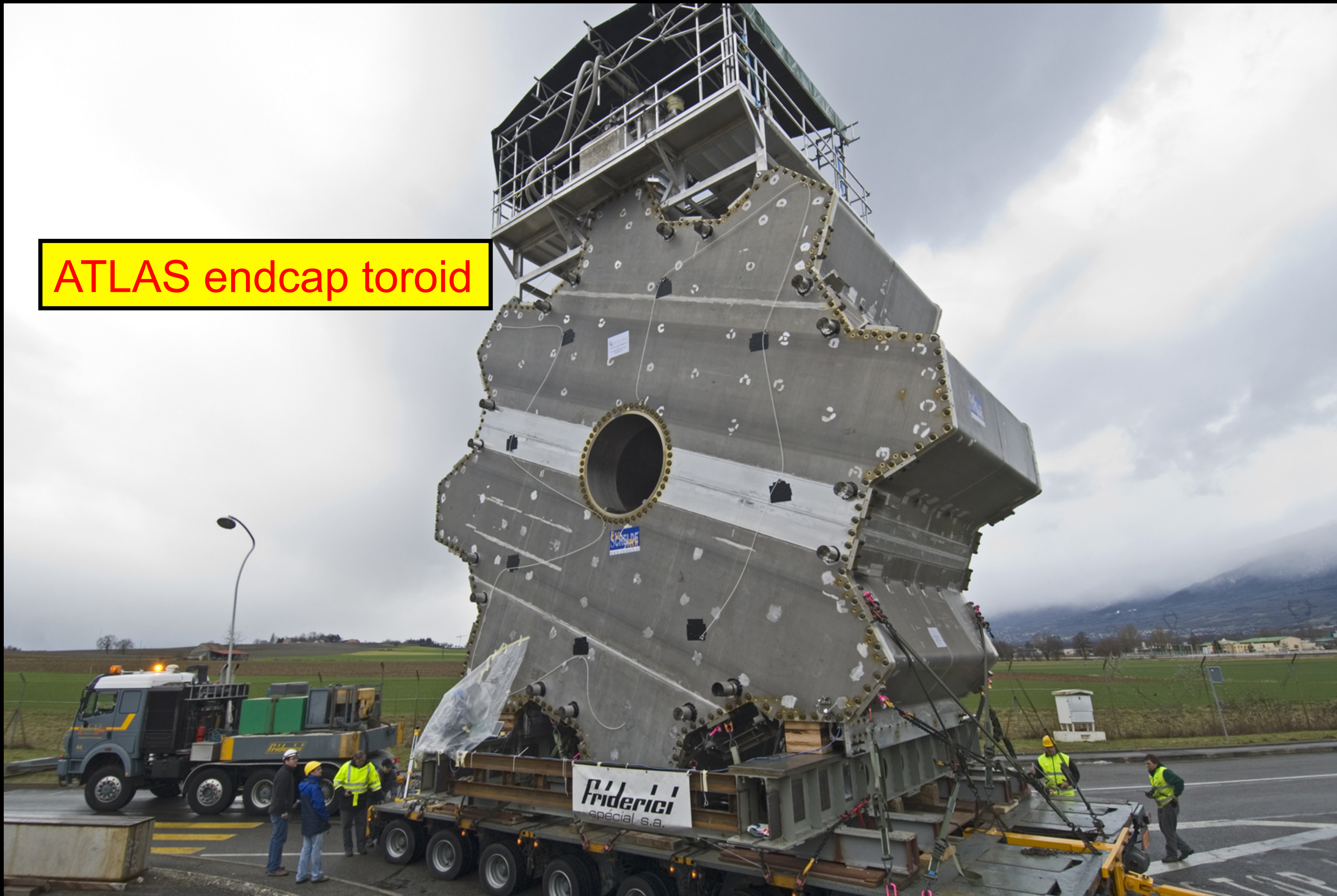
Looking down to dimensions of ~10^{-19} m

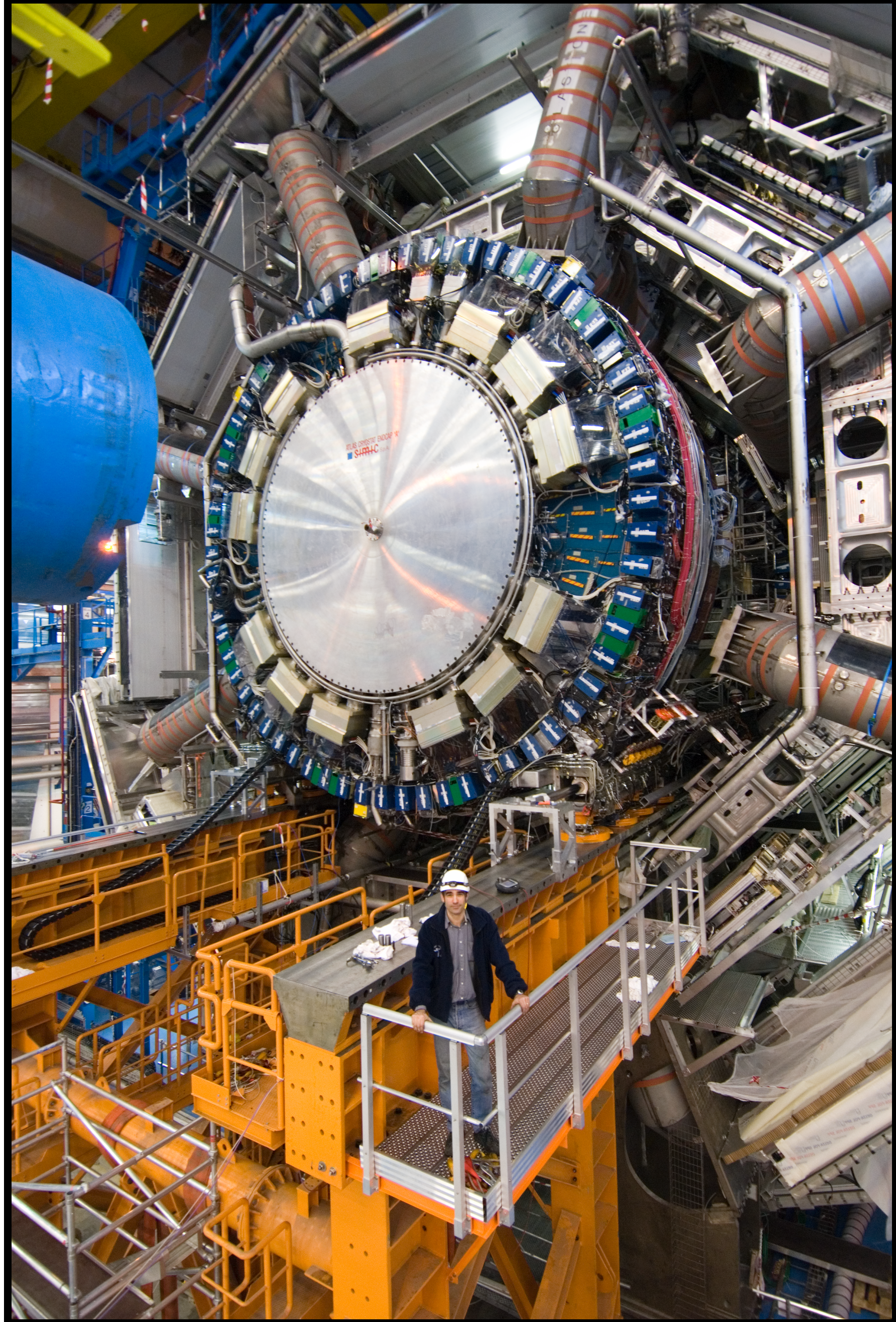


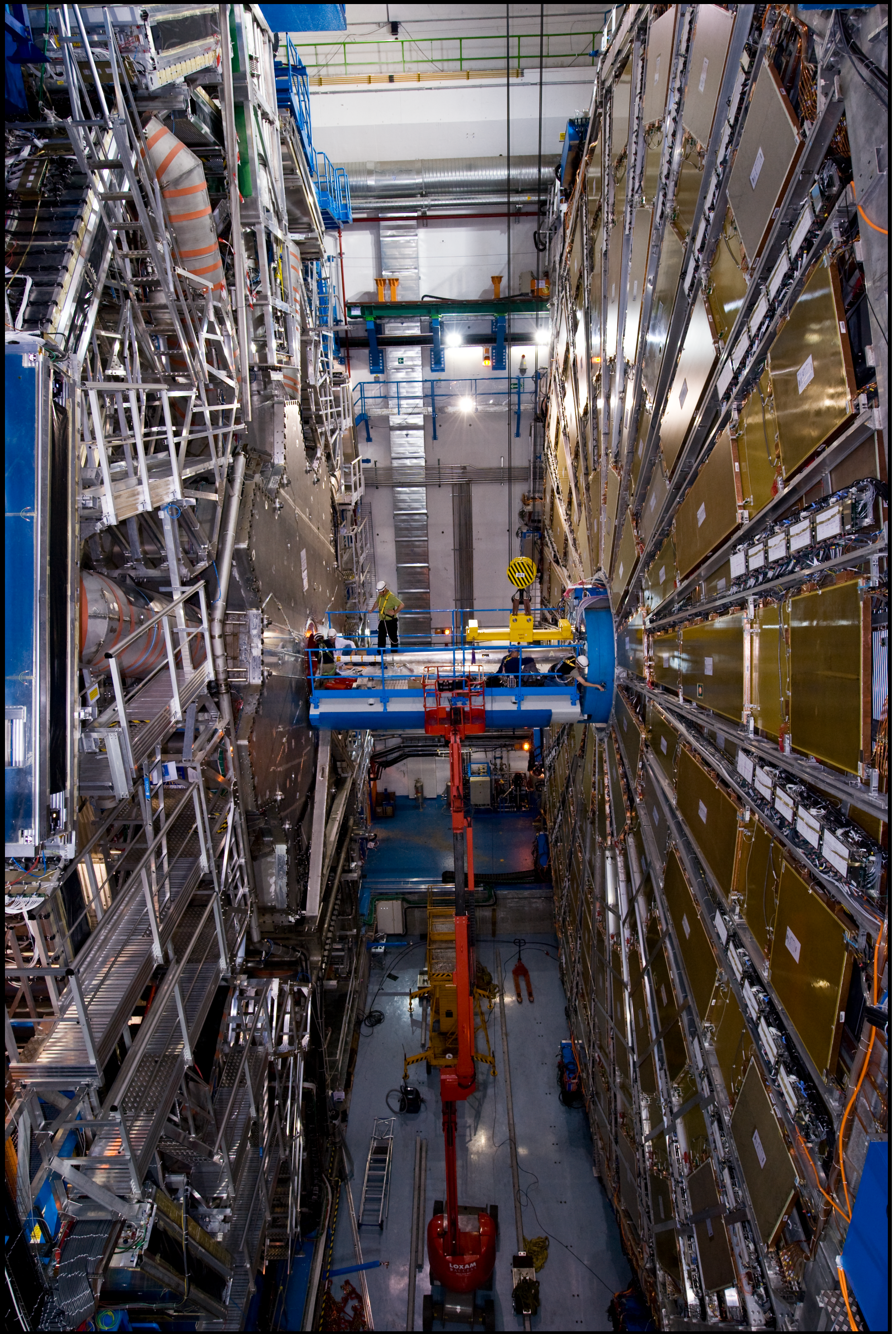
Solenoid field: 2.6 T
Toroid field: 4T
7000 Tonnes

UNIVERSITA' degli STUDI di ROMA
TOR VERGATA

ATLAS endcap toroid

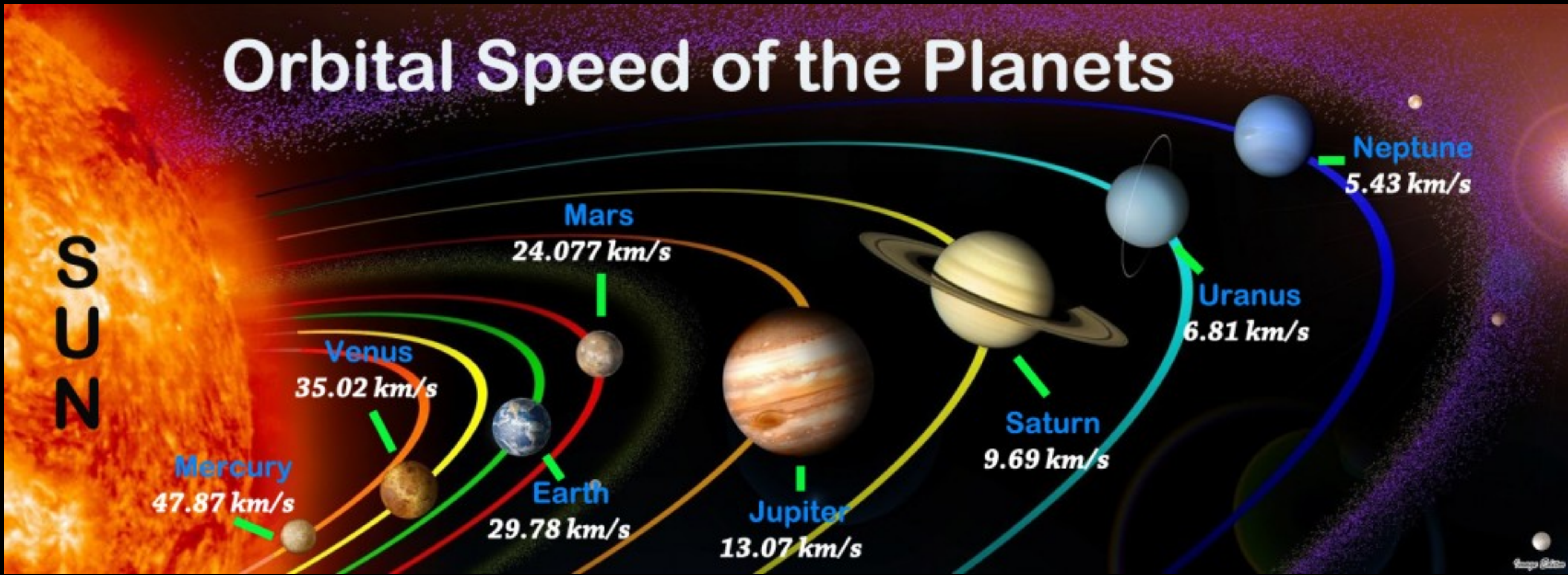




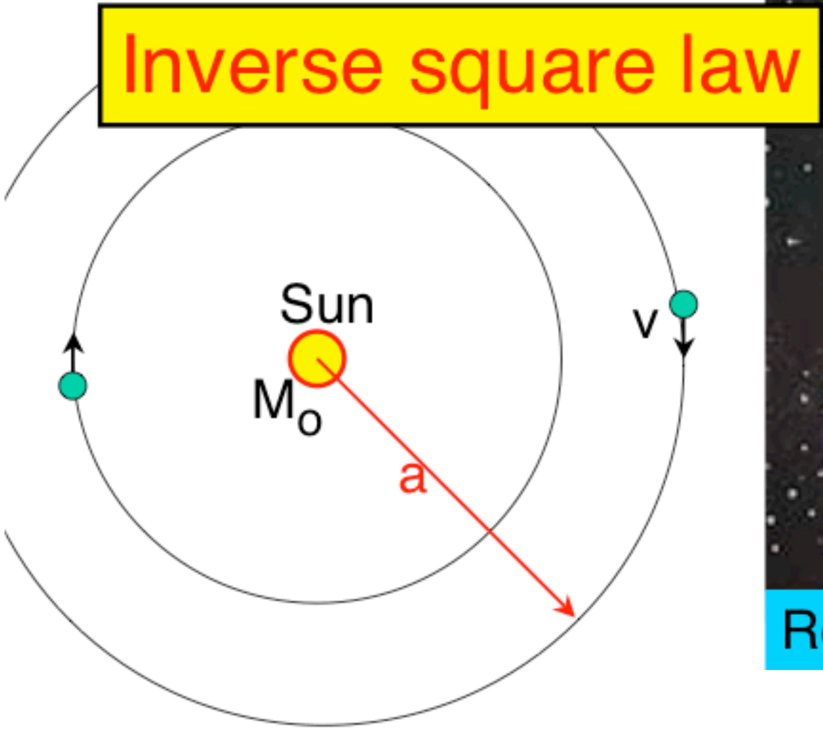



Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration
July 2010

Disappeared. Invisible. Unexpected.


Orbital Speed of the Planets
SUN
Mercury
47.87 km/s
Venus
35.02 km/s
Earth
29.78 km/s
Mars
24.077 km/s
Jupiter
13.07 km/s
Saturn
9.69 km/s
Uranus
6.81 km/s
Neptune
5.43 km/s

What Keeps Galaxies Together ?

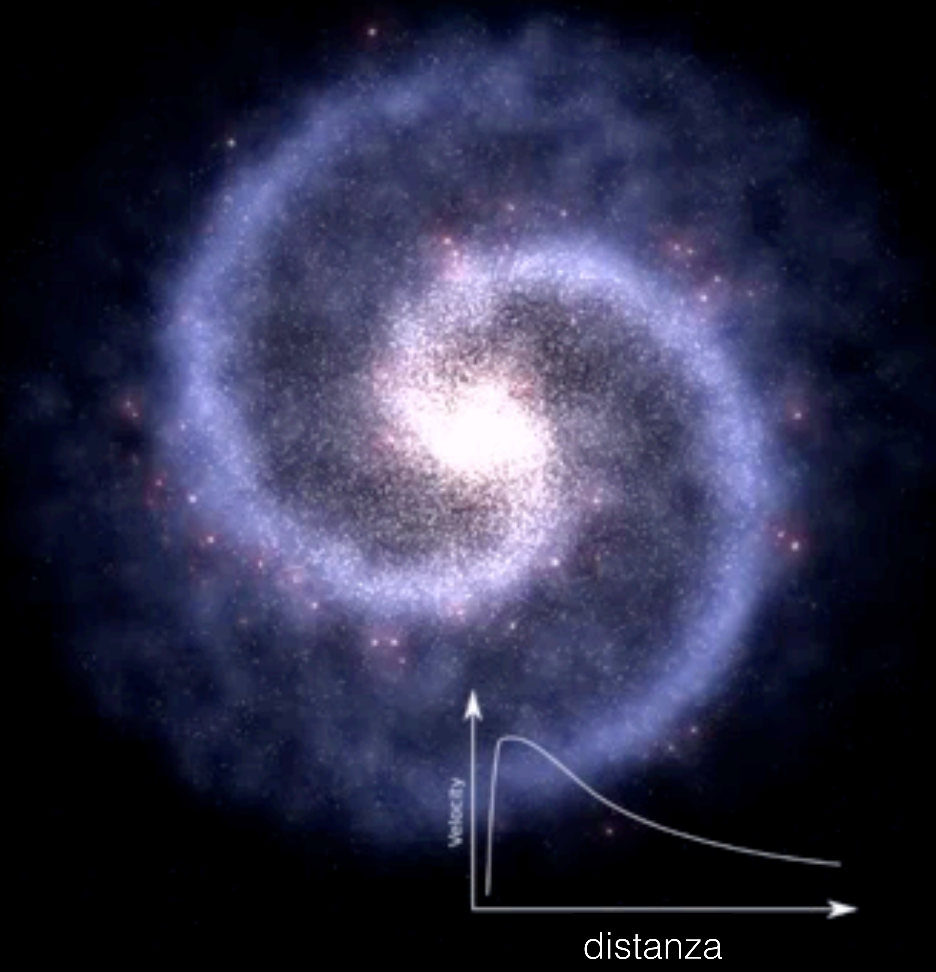


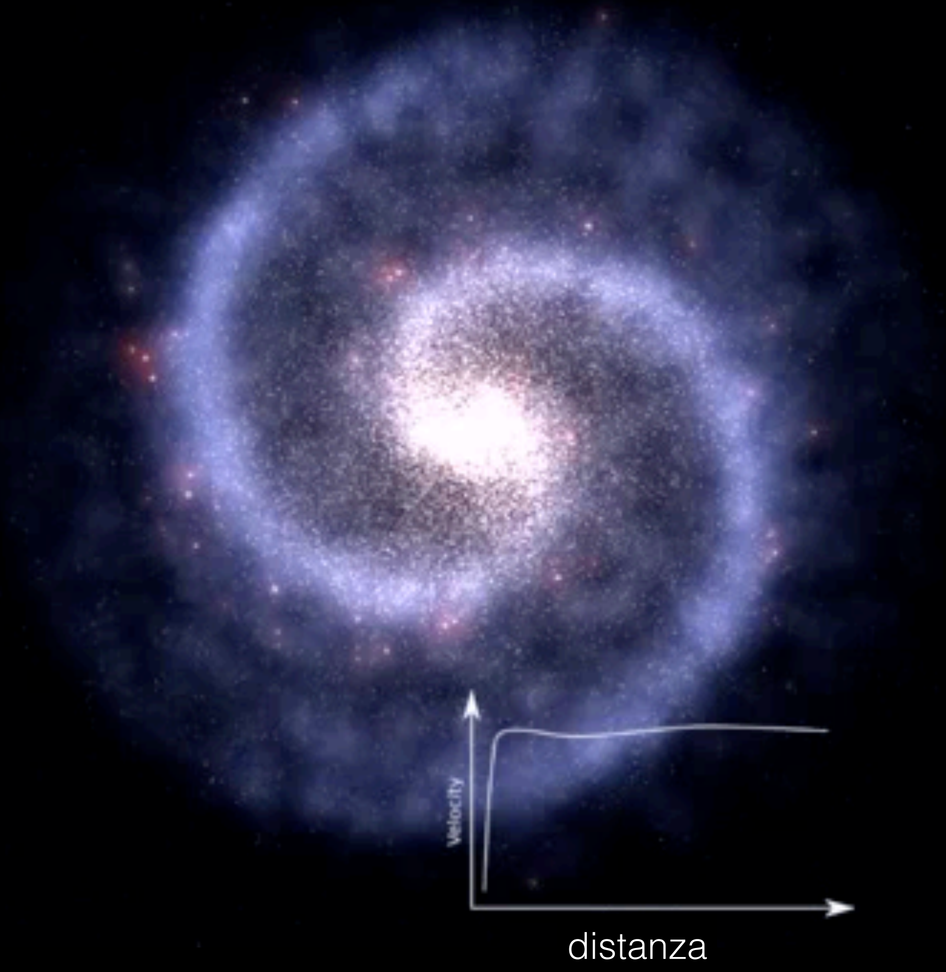
Rotation in spiral galaxies

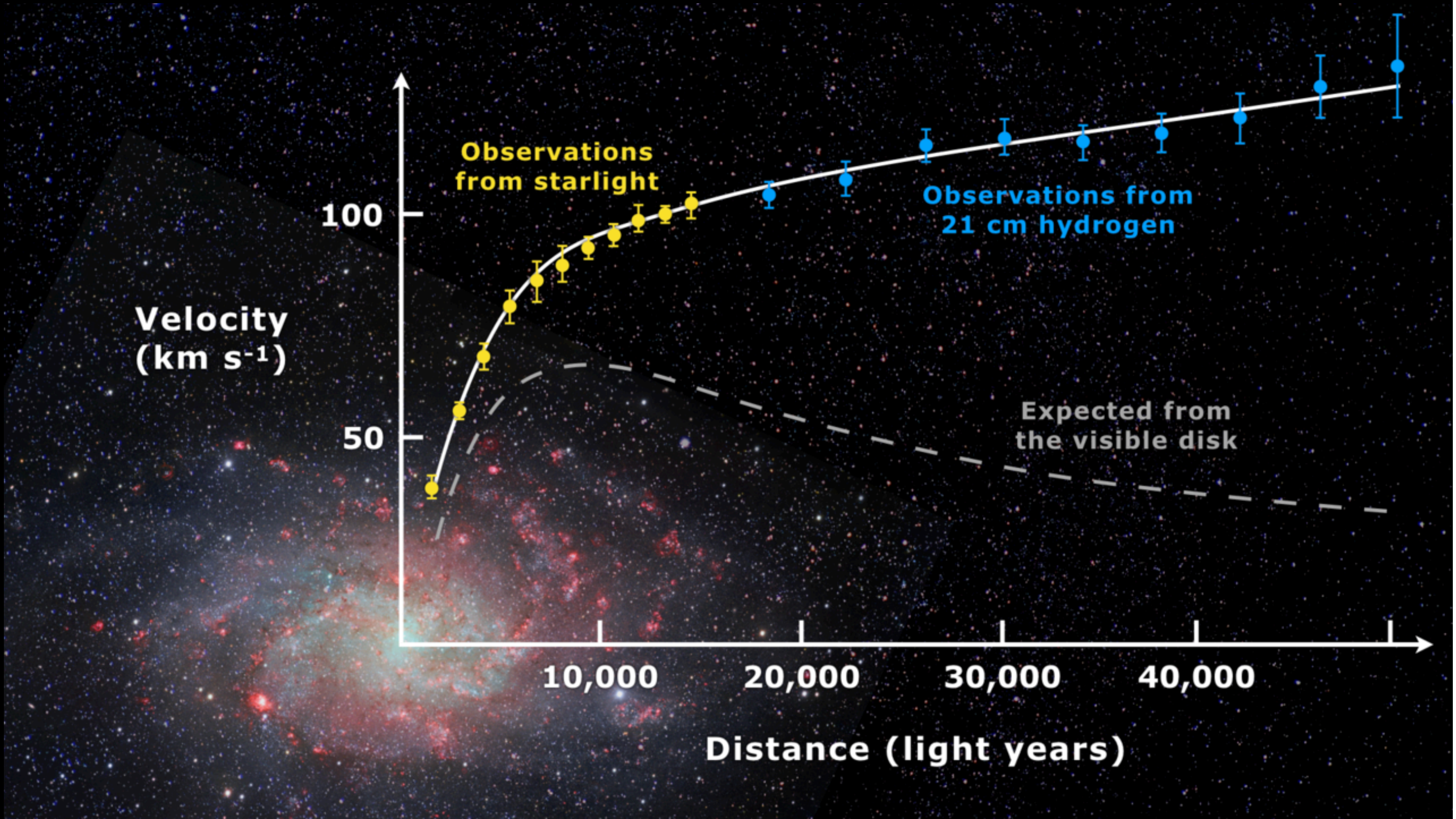
Kepler, Newton

$$T^2 = 4\pi^2 a^3 / G M_o$$

$$v^2 = G M_o / a \text{ (circular orbit)}$$


Velocity
distanza


Velocity
distanza



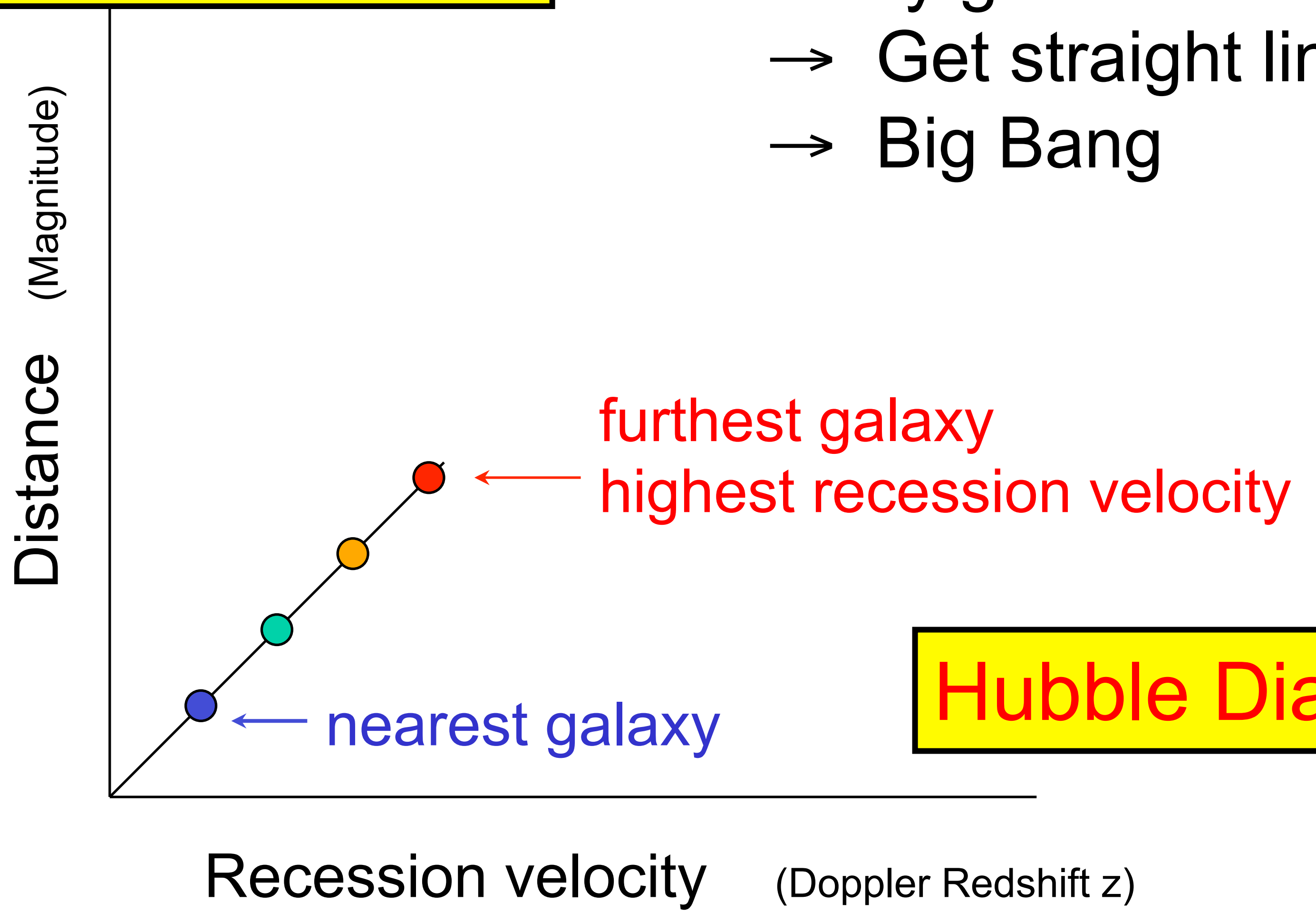
Hence there is more gravitationally attractive material than is being detected:

"DARK MATTER"

5:1

The Universe is like this !

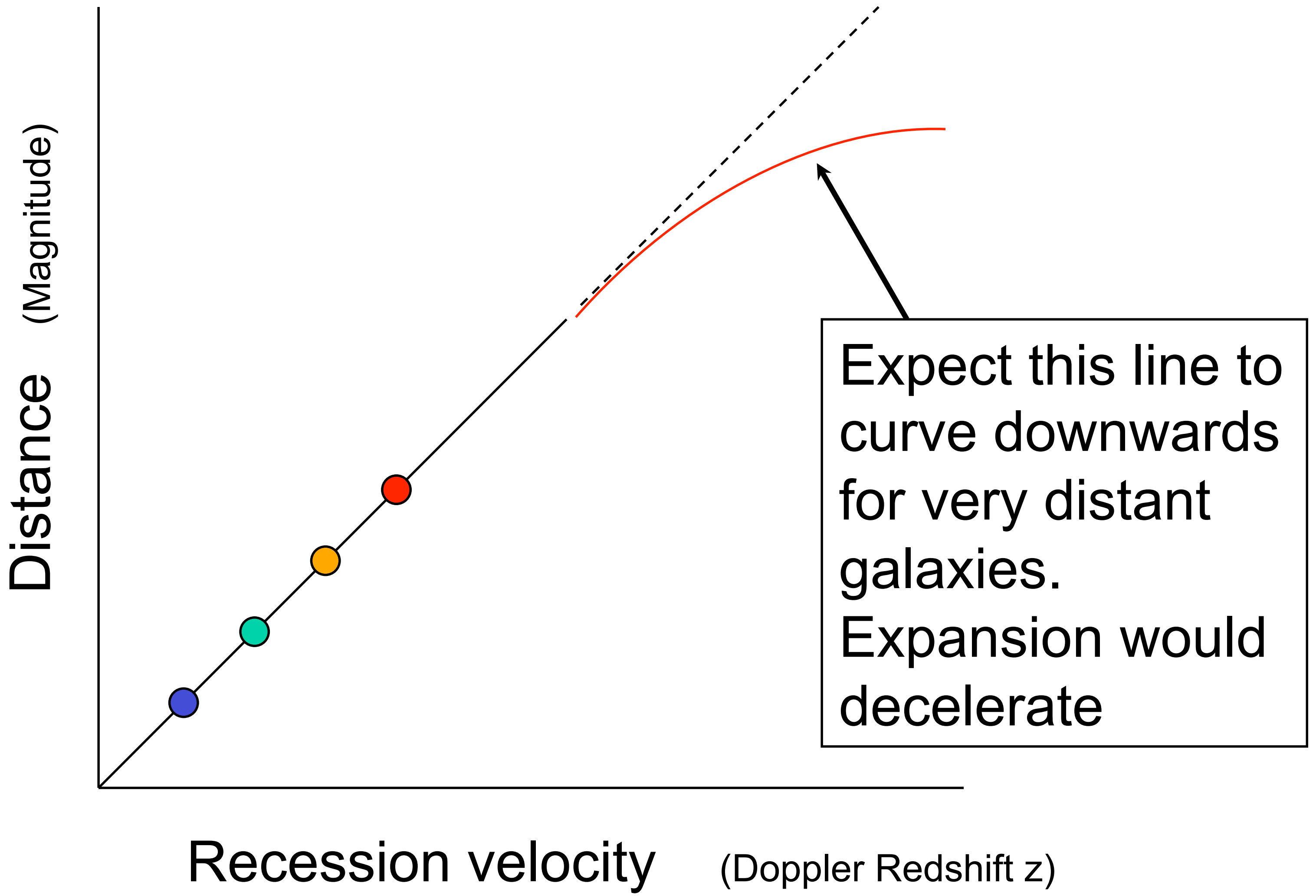
Plot distance against recession velocity for many galaxies
→ Get straight line
→ Big Bang



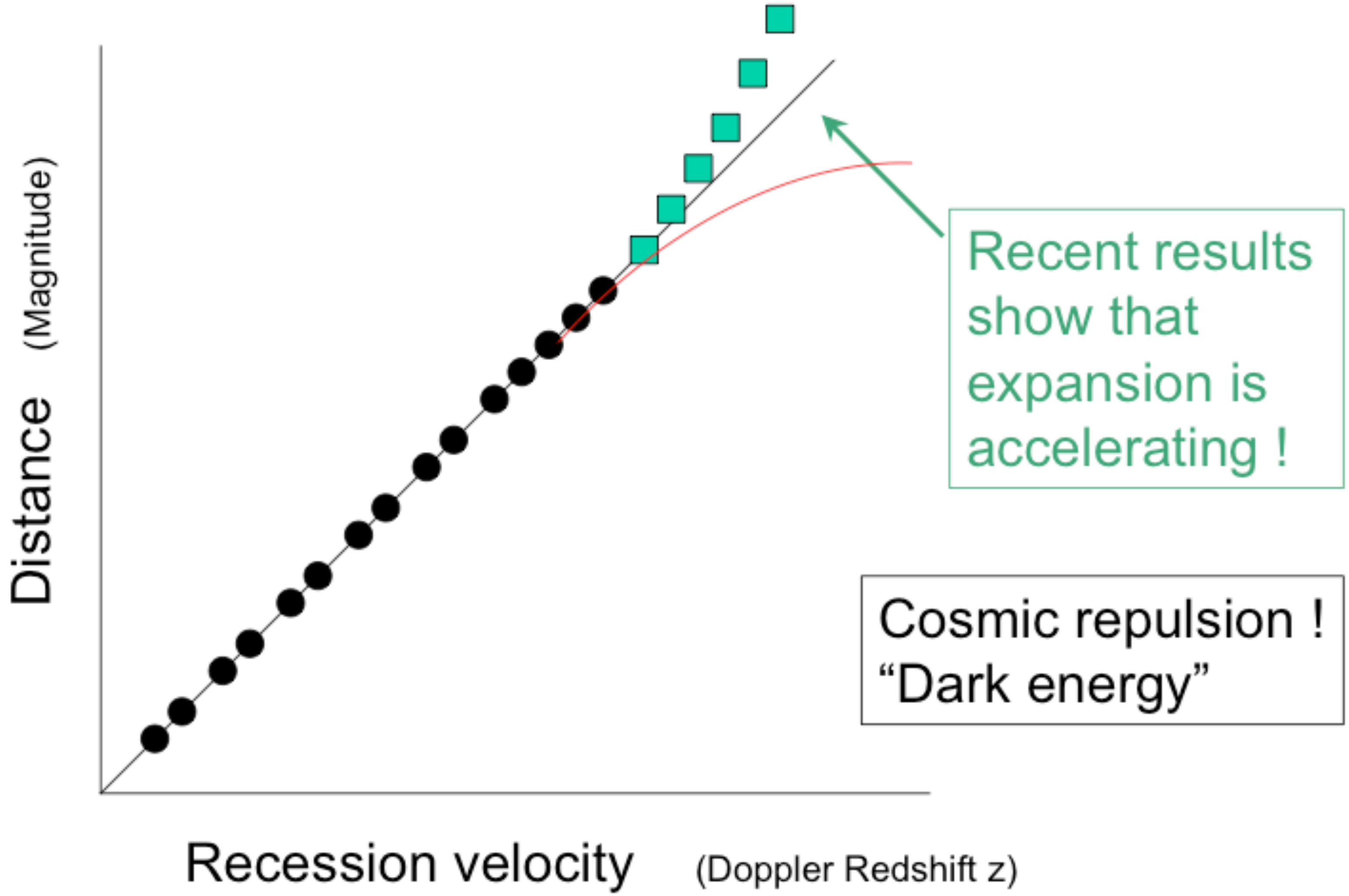
Hubble Diagram

Hubble Diagram

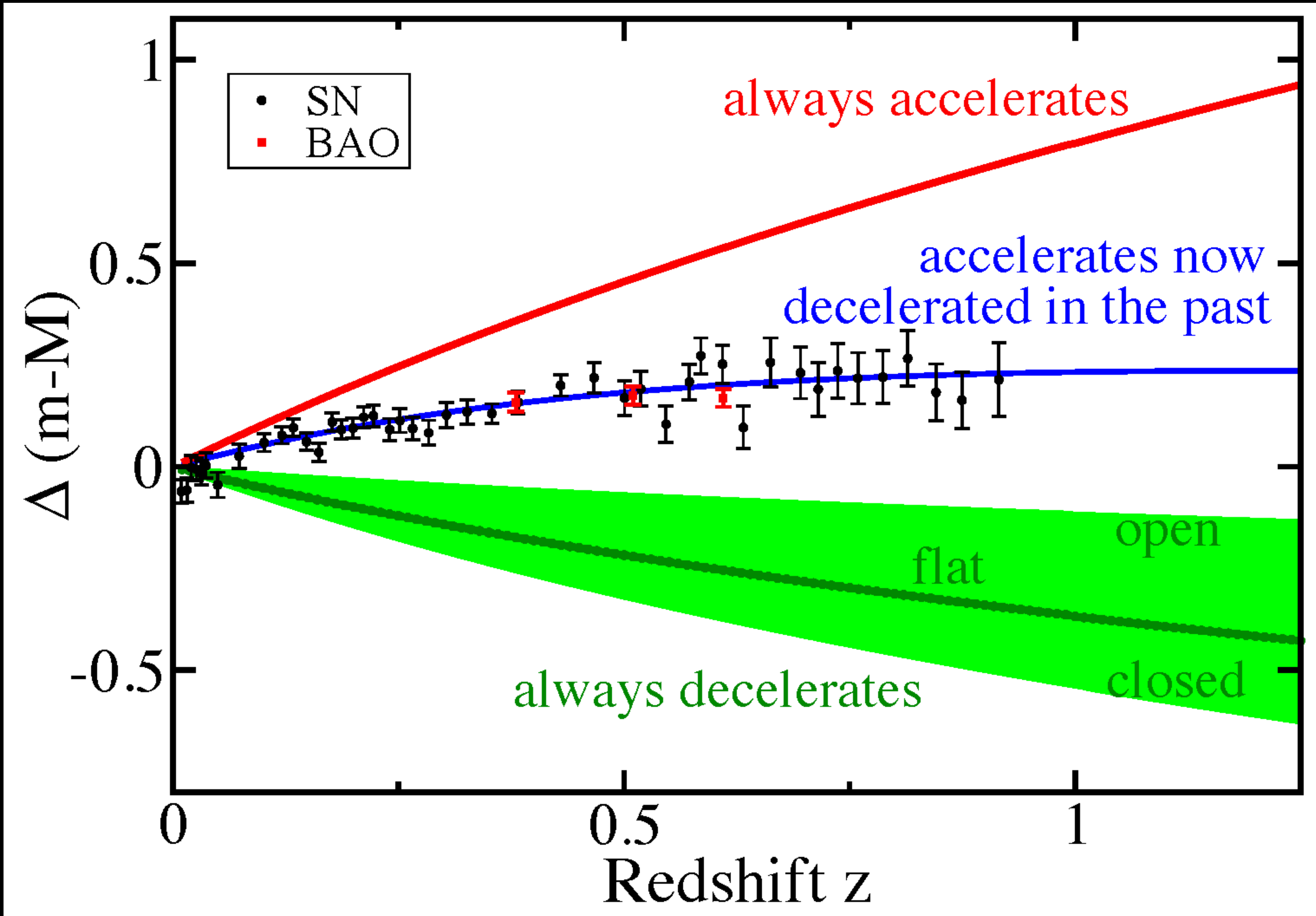
But cannot ignore gravity which slows down the flow



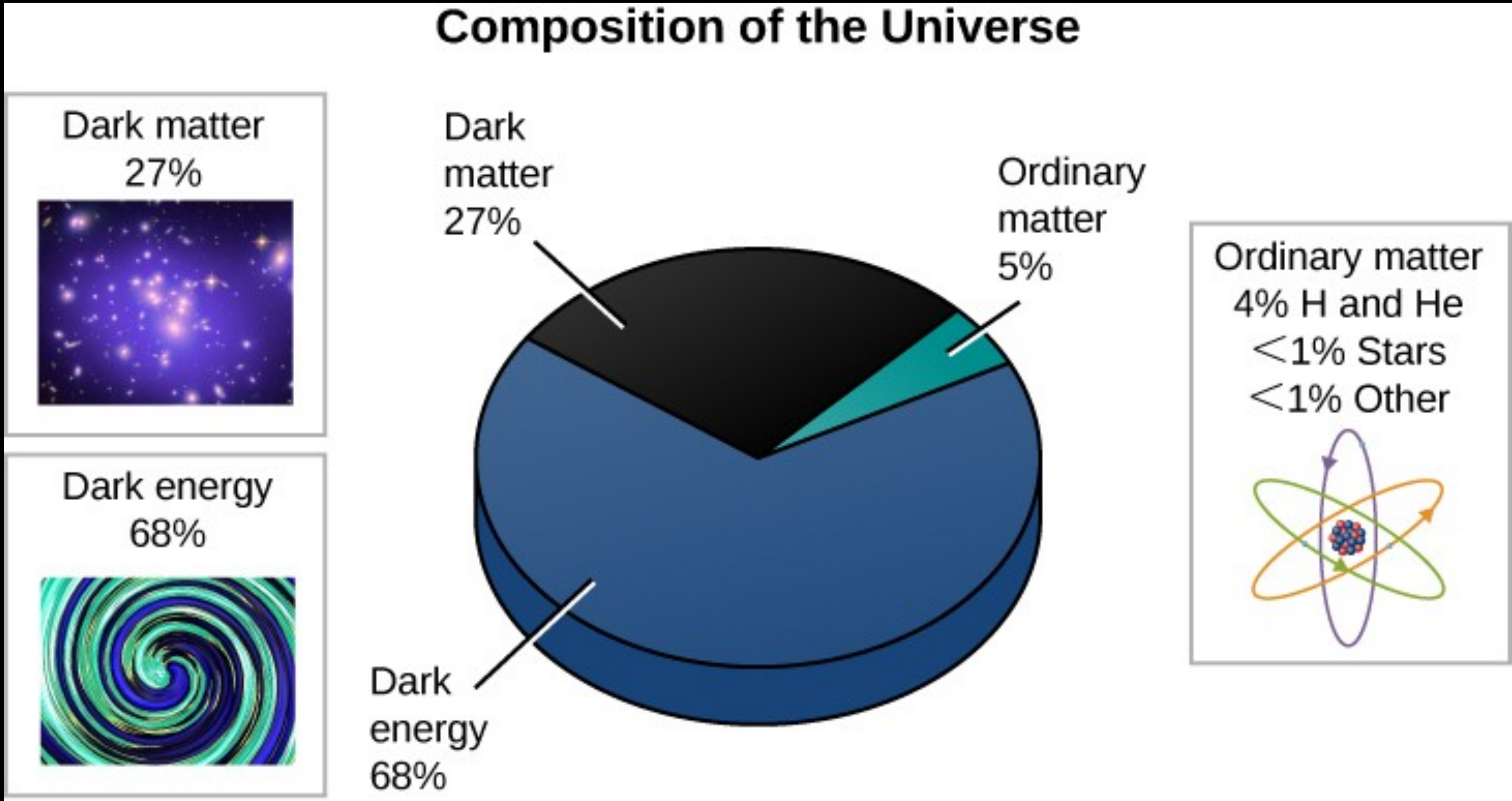
Hubble Diagram (simplified)



Cosmic repulsion !
“Dark energy”



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


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

Images and Videos: Credit CERN