

Conceptual Changes in the Understanding of Nature

Concepts of Interest

- The Quantum of Energy
- Space -Time -Mass
- Gravity
- ‘Quantum’ Description of Nature
- ‘Standard Model’ of Natural Forces
- Cosmology and Origin of the Universe

Galileo

16th Century

- The Earth rotates around the Sun.
- Experiment is Central to Discovery

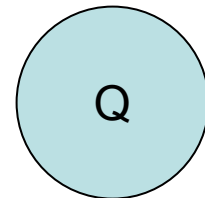
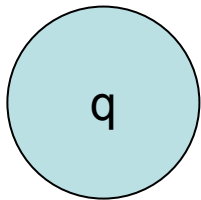
Medium distance Physics

1900

Action at a Distance

- Newton's laws
- Maxwell's equations

◦ q_1



Inverse Square Laws

$$F \sim M m / R^2$$

$$F \sim Q q / R^2$$

Space & Time

- Space is three dimensional (Up –Right-forward ...and opposite directions)
- Time is absolute
- All phenomena are taking place on this ‘stage’ as time ‘flows’.
- Action at a distance implies Infinite speeds

Puzzles

- **Black Body Radiation:** No explanation for its 'spectrum'
- **The Michelson Morley Experiment:** speed of light is **Finite** and **independent** of the speed of the source in contrast to every thing else.....

The Quantum of light

Proposal by
Planck

That E&M energy in light is carried in packages
each with amount:

$$E = h \times \text{frequency of light}$$

With $h =$ universal constant (Planck constant)!

The 'Photon' is introduced

1905

Proposal by Einstein that the
Speed of light is constant for all inertial
observers
(i.e. for observers moving with relative
CONSTANT velocities to each other)

Space -Time

Space Time is four dimensional
(3 space + 1 time)

Time and Space may be exchanged
(Like coordinates of a vector)

Space-Time: Cont'd

Time and Space **intervals** (time differences and lengths) may then transform (i.e. as seen by different observers) into each other and so would many 'Physical' observable quantities !

Examples:

Time dilatation

two 'events' at the same place as seen by one observer at times t_1 and then t_2 are separated by a time interval of :

$$T = t_2 - t_1$$

Would appear for another observer at times

$$T' = t_2' - t_1' = \gamma (t_2 - t_1)$$

$$\text{with } \gamma > 1$$

Space Contraction

If we consider two events at the same time but at different positions x_1 and x_2 the 'space' separation for one observer which is

$$L = x_2 - x_1$$

Will appear for the moving observer as

$$L' = x_2' - x_1' = L / \gamma < L$$

Time and Space

Time and Space 'intervals' separating two 'events' then acquire a new meaning and are dependent on the relative speeds of observers of these events.

and

There is no absolute space time !

Momentum and Energy are also dependent on distances and time (velocities) and their values (components) do transform into each other!

they form a 'four dimensional vector'

Energy Momentum four vector

$$(Pc, E)$$

length preserved

$$P^2c^2 - E^2 = P'^2c^2 - E'^2$$

For $P=0$

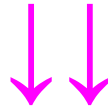
'rest' energy is :

$$E = mc^2$$

Mass is a measure of rest Energy



Mass and Energy may be
interchanged!



Understanding radioactivity and
fission

Pair Production and Annihilation

Photons (light) may change to massive objects (particles)!



Electron positron pairs (particles) may Annihilate and produce two photons (light)



1916: General Relativity

Principle of Equivalence

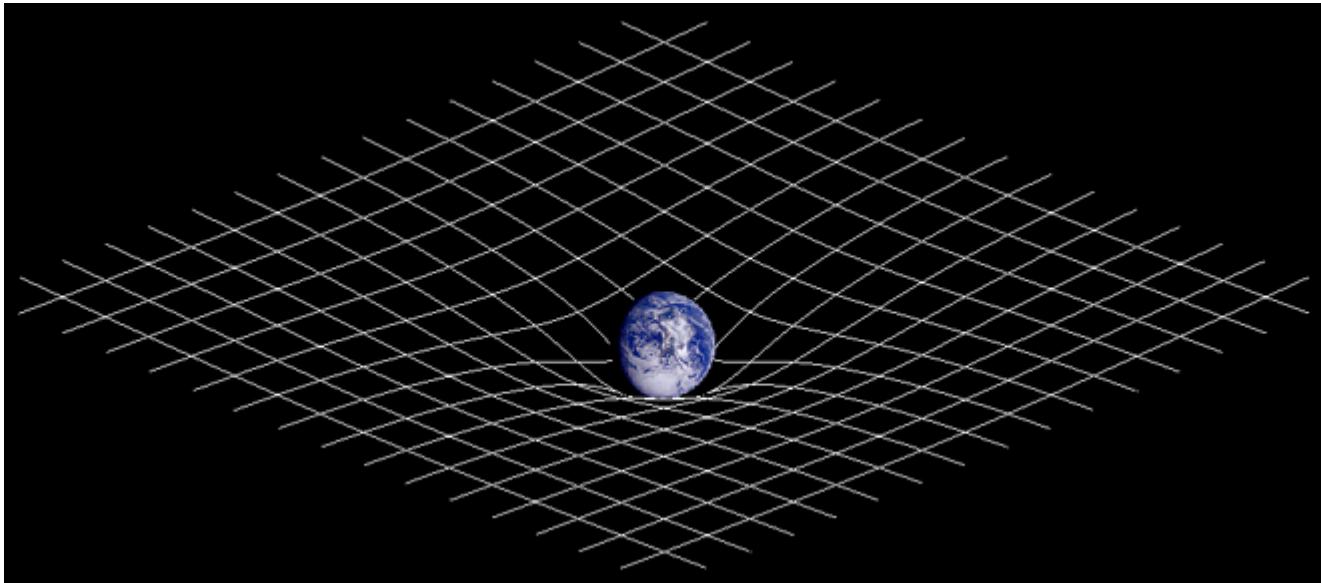
Gravitational field indistinguishable from being in an 'accelerated' frame of reference !

Curved Space Time

Accelerated frames may be represented
mathematically by
'curved space times'
and hence so would the effect of a
gravitational field!

Geometry and the Gravitational Force are ONE!

Gravitational forces are an effect seen as motion along geodesics of a curved space time



Other large scale consequences

Einstein equations imply that **space** and **time** and their **Geometry** are **dynamical variables!**



UNIVERSE is not STATIC!

Effects

Bending of light in a gravitational field (yes)

Extreme case : Black holes! (yes)

'Ripples' in the Curved Geometry leads to
Gravitational waves! (not yet)

(counterpart to EM waves!)

Expansion ? Contraction?

Observations show that the Universe is
EXPANDING !

Distances between its constituents is
increasing as measured by the

RED shift

of the spectrum of light received for distant
objects!

Origin?

An expanding Universe must have started
from a smaller universe

A BIG BANG!?

Estimated 'age' can be determined by the
distance of the farthest objects

Current estimate

15 Billion years

Physics at short distances then is important to study the
ORIGIN of the UNIVERSE

it is clearly also important for the studying the structure of

ATOMS and NUCLEI !



Quantum Mechanics

Quantum Mechanics

1925-1926

- No trajectories but Quantum States !
- No complete predictability of ALL Physical variables: Uncertainty Principle
- Physical information is 'statistical' in nature

!

Quantum Mechanics

1. Physical systems exist in well defined states identified by some measurable quantities such as energy, angular momentum etc....
2. Systems transform themselves between these states with predictable 'probabilities'.
3. One can 'fix' the state of a system only 'after' a measurement.
4. 'Likelihood' of the system to exist in other states after that can be calculated using 'quantum mechanical' equations of 'motion' of such states.
5. 'Classical' quantities need not be all precisely known in a particular state: uncertainty relations exist!

1926: Relativistic QM

Dirac equation combines QM with Special Relativity



Prediction of **ANTI MATTER**



Discovery of Positron (e^+), anti-proton (p^-)
Anti-neutron (n^0), etc.....

Further developments of Relativistic Quantum Mechanics

The study of general interactions of EM radiation (photons) with Matter (electrons , protons etc...) necessitated the invention of methods to generalize the Dirac equation to many (infinite!) 'particle' systems.



Quantum Field Theories of particle interactions

Characteristics

- All interactions are point like !
- Interactions involve multitude of processes
- The net effect is obtained as a result of the collective effect of all such interactions.

Point Interactions

Photon emission by e^-



Photon absorption by e^-



Photon emission by e^+

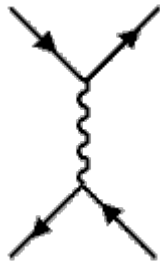


Photon absorption by e^+



Scattering

$e^- e^+$ Scattering: lowest order



- Pair Production



- Pair Annihilation



General Interactions

Higher order $e - e^+$ Scattering



Even Shorter Distances

Nuclear Forces

These are responsible for binding the Nucleus

Weak Forces

Responsible for decay of neutrons to protons
(among other things!)



Change of the nature of matter

The nature of such interactions is just the same as Electron Photon Interactions but more Complicated and

Involve a large number of particles

The Standard Model

1967-1972

The fundamental particles come in two general categories:

1. Matter particles which carry mass
2. Radiation which has mass = 0

Massive particles

- These come in two classes:
- Quarks that are constituents of 'hadrons' (protons, neutrons ,etc...)
- Leptons (electrons, muons)

Quarks

Quarks come in
six
flavors and
three
colors!

- u d s

u d s

u d s

- c t b

c t b

c t b

- AND carry fractional Electric Charge $\pm 1/3, \pm 2/3 e$

Leptons

Leptons carry a characteristic known as lepton number and come in also

six

families

but

These particles carry integral charges $\pm e$

Each family has associated with it a (massive ?) Neutrino

Mass-less particles

Gluons

(g)

These are 8 photon like objects that carry a 'color' and an 'anti-color' each and couple only to 'color'

Weak Bosons

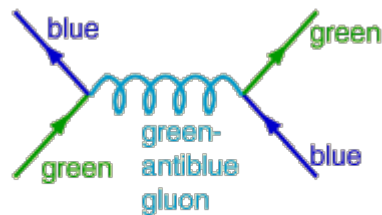
(W^+ , W^- , Z^0)

These are three that couple to leptons and quarks
They acquire heavy masses due symmetry breaking by
“Higgs Boson”

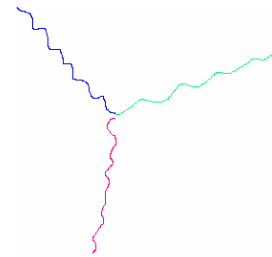
Interactions

Gluons

Interaction is point like and takes the following forms



Feynman diagram for an interaction between quarks generated by a gluon.

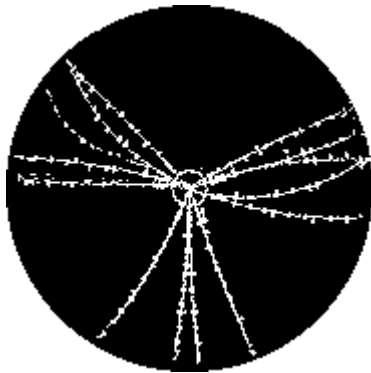


leads to a stronger force as the distance increases !

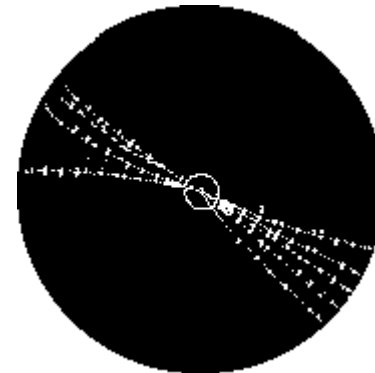
This 'strong' force is 'confining'.....NO escape for Quarks or Gluons !

Detection of gluons and Quarks

Gluons \rightarrow 3 jets



Quark events \rightarrow 2 Jets



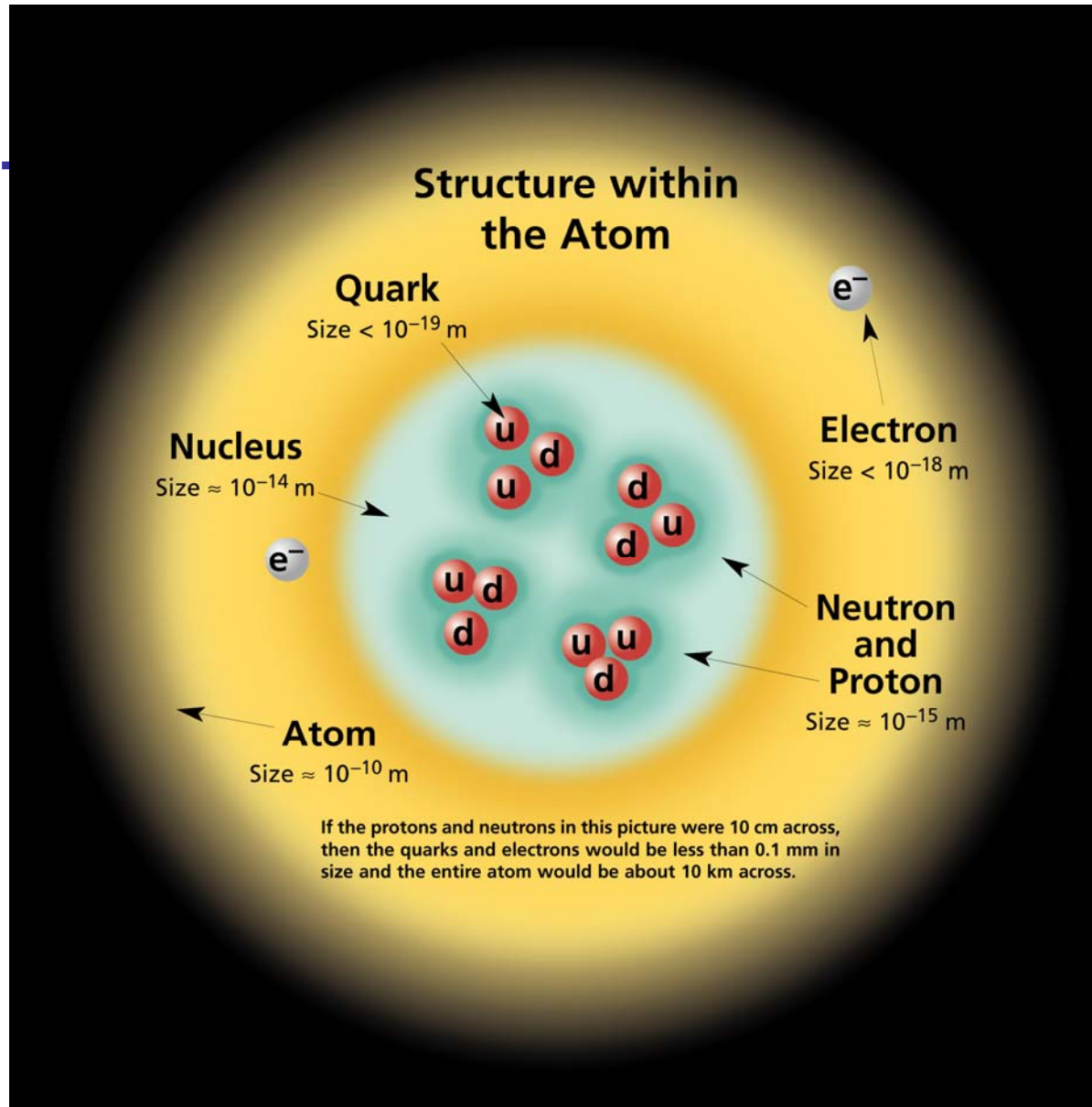
Hadron (proton , Neutron etc...)

Structure

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Structure of Atoms

Atoms...



Mesons

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Forces

Mediators :

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at:	10^{-41}	0.8	1	25	Not applicable to quarks
	10^{-41}	10^{-4}	1	60	
	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

BOSONS

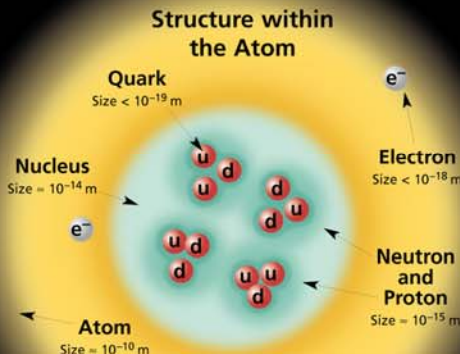
force carriers
spin = 0, 1, 2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	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

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq .

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c² = 1.67×10^{-27} kg.

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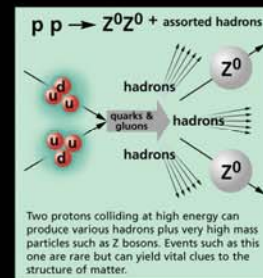
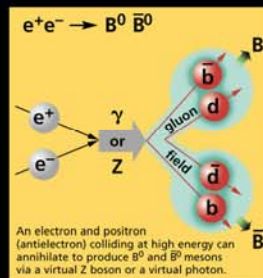
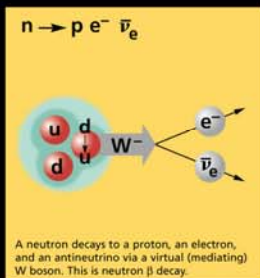
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Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless s or $-$ charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0 , γ , and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

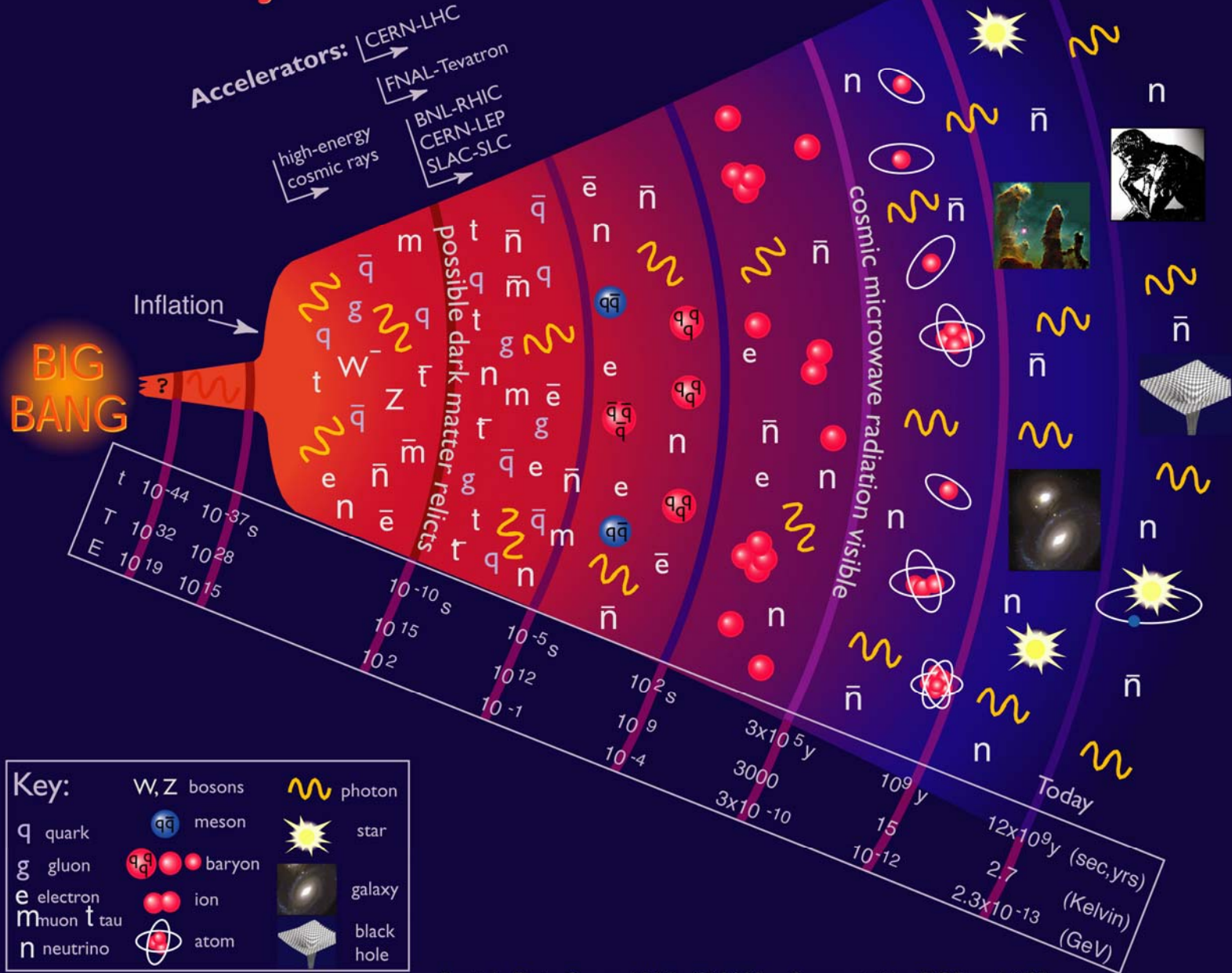
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History of the Universe



Strings?

The current pictures is experimentally verified ..but TOO complicated !!

Is there a simpler set of fundamental constituents?

Strings (two dimensional objects) may provide the answer

Indicators

Strings seem to point the way to a
UNIFICATION of **Gravity** with the
Standard Model

The good news ...

A lot left for you to Pursue