Introduction to Elementary Particle Physics

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Abstract. This is a short review of Particle Physics and the most widely accepted theory, the Standard Model, with its questions and limitations. We also show a quick review of some of te theories beyonf the Standard Model. It is based in the introductory talk given the Third School on Cosmic Rays and Astrophysics held in Arequipa, Peru.

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The Universe is made of elementary particles, ruled by a few fundamental forces of nature. Some of these particles are stable, but some of them just have a lifetime of a fraction of second. It's said that all these particles coexisted together during the Big Bang.

Particle Physics is the study of the basic nature of energy, of matter, of force, of time or space. It works on discovery the simplest constituents of matter (elementary particles), and to understand the fundamental forces interacting among them.

Elementary Particles are too small to see or study directly, so we examine them by colliding particles at high energies and analyzing the results. Currently, those energies are possible just in big accelerators like the ones at CERN or FERMILAB.

As far as we known, elementary particles experience four types of forces:

- **Gravitational Force:** This is an attraction force between two particles and it's proportional to their masses. This force controls the motion of planets and galaxies and determines the law of gravity.
- **Electromagnetic Force:** It's the combination of electrostatic and magnetic forces. It acts between any two electrally charged particles, such as the force between an electron and a proton. This force is responsible for holding atoms together, and most of the phenomena we experience in life everyday.
- **Weak Nuclear Force:** It mediates beta decay and is transferred by W and Z bosons. Neutrinos interact with other matter only through this force and gravity, hence, it can penetrate large amounts of matter without being scattered.
  This force along with the electromagnetic, form what is called the **Electroweak force**.
- **Strong Nuclear Force:** This force is responsible for holding together the protons and neutrons inside the atomic nucleus.The strong force holds quarks together to form hadrons.

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TABLE 1. The elementary particles (fermions) known [1]: the quarks and leptons. The corresponding anti-particles have opposite charge.

symbol	mass $[MeV/c^2]$	q/lel	symbol	mass $[MeV/c^2]$	q/lel
u (up)	1.5 to 3.3	$+2/3$	e^- (electron)	0.510998910	-1
d (down)	3.5 to 6.0	$-1/3$	ν_e (electron neutrino)	< 0.0000022	0
c (charm)	$1,270^{+70}_{-110}$	$+2/3$	μ^- (muon)	105.6583668	-1
s (strange)	104^{+26}_{-34}	$-1/3$	ν_μ (muon neutrino)	< 0.17	0
t (top)	$171,200 \pm 2,100$	$+2/3$	τ^- (tauon)	1,776.84	-1
b (bottom)	$4,200^{+170}_{-70}$	$-1/3$	ν_τ (tauon neutrino)	yet unknown	0

THE STANDARD MODEL

All the particles and their interactions (except the Gravitational one) observed to date can almost be described entirely by a quantum field theory called the Standard Model. The Standard Model has 17 species of elementary particles (12 fermions (24 if you count antiparticles separately), 4 vector bosons (5 if you count antiparticles separately), and 1 scalar bosons), which can combine to form composite particles, accounting for the hundreds of other species of particles discovered until now.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles

The Standard Model Particles and Forces are composed of **Fundamental Particles (Fermions)** organized in three families of quarks and leptons (see table 1). They are six quarks (u, d, s, c, b, t) and six leptons (e, μ, τ, ν_e, ν_μ, ν_τ) organized in three families. The bosons of exchanging force are: γ, $W^\pm$, Z^0 and 8 gluons.

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$
$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Quarks have interesting characteristics, such as having a fractional electrical charge, and they actually carry another type of charge, which is called *color charge*.

Hadrons: Though quarks have fractional electrical charges, once they combine each other, they form hadrons in such a way that have an integer electric charge. Another characteristic of hadrons is that they doesn't have color charge as quarks.

There are two types of hadrons: *baryons*, which are made of three quarks (i.e: protons are made of two up quarks and one down quark) and *mesons*, made of one quark and one antiquark (i.e: the J/ψ particle is made of a charm quark and a charm antiquark).

It can be said, that leptons are lonely particles, rather than quarks that are *sociable* particles, and they only exists together compounding hadrons. Each charged lepton has a neutrino part associated, and each lepton has an antilepton, being the electron, the only one whose antiparticle - the *anti-electron* - has a particular name: *the positron*.

Muon and Tau leptons, can't be found in ordinary matter since when they are produced, they decay very quickly, or transforms in lighter leptons. When a lepton decays, one of the "sons" is always its corresponding neutrino, and the other particles can be a quark and its antiquark, or another lepton and antineutrino.

It's been observed that some lepton decays are possible and some others not, to explain this, three lepton families have been created.

The *number* of members in each one of the families (muon number, tau number, electron number) remains constant in a decay (i.e: a particle and its antiparticle in the same famility *cancel out*, and so they count as zero).

So for example, in the next decay:

$$\tau \rightarrow \nu_\tau + e^- + \bar{\nu}_e$$

We have in the *left* side of the decay +1 for the *tau number*. In the right side we have also +1 for tau number because of the ν_τ, and the sum of $e- = 1$ and $\bar{\nu}_e = -1$ is zero for the electron number. So muon, electron and tau numbers are conserved (tau number=1, electron and muon number = 0 in both sides). This law is one of the rules used to know if a lepton decay is possible, another law used is the energy conservation. For example the next decay:

$$e^- \rightarrow \mu + \bar{\nu}_\mu + \nu_e$$

obey the number conservation in each family (electron number=1, tau and muon number=0 in both sides), but the decay is still not possible due to the fact that muons are a lot more massive than electrons, hence energy is not conserved.

Fundamental Forces (Bosons):

Interaction	**Mediator**	**Spin/Parity**
Strong Nuclear Force	8 gluons	1^-
Weak Nuclear Force	W^+, W^-, Z^0	$1^-, 1^+$
Electromagnetic Force	γ	1^-
Higgs Boson?	H (not yet discovered)	?

gluons: As we said, quarks are color charged particles, and the force between color charged particles is very strong (main reason for the name "strong nuclear force"). Its carrier particles are called *gluons* (which are color charged particles too),

In strong interactions, gluons are exchanged by quarks creating a color *color force field* binding those quarks together, which is the reason for quarks not existing alone, since the color force increase as they are pulled apart.

Particle Decays and Annhilations

The standard model can explain why and how particles decays into another ones.

There is a principal difference between nuclear an particle decays. In nuclear decays, an atomic nucleus can decay into smaller nuclei, but decay of fundamental particles means, they *turns* into another fundamental particle (since rather than atoms, fundamental particles don't have constituents).

When a fundamental particle decays, the new particle it turns into is a less massive particle, and there is a carrier-force (W boson for fundamental particles decays) also, that exist only for a very short instant and then originate another particles.

Carrier-forces seems to violate conservation of energy at first instant, but they don't, because of Heisenberg's uncertainty principle:

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

this can be expressed in terms of energy and time, $\Delta \tau \Delta E \geq \frac{\hbar}{2}$, which means that, for very short-live particles, the *energy uncertainty* can be really big, letting us introduce the idea of **virtual particles**.

Energy conservation is not violated, the kinetic energy plus the original mass of the particle is equal to the mass of the final products decays, virtual particles exist so briefly that can't be observed.

The fundamental forces (electromagnetic, weak and strong force) originate all decays, however, the weak force is the only one responsible of fundamental particle decays through W^+, W^- bosons, so weak force cause which is called **change of flavor** (i.e: up and down quarks are flavors, so they can change into the other because of weak interactions, note that their electric charge change also).

Strong Force cause **changes of color** without electric changes using gluons as mediators, and electromagnetic force

Annhilations:

This is when a matter and an antimatter particle annhilate each other producing pure energy, which produce a very energetic force-carrier particle (gluons, W/Z bosons, or a photon), which originate new particles.

Annhilation is a common method in physics to produce new massive particles, for example the Tevatron Accelerator in Fermilab (figure 3) annhilates protons an antiprotons.

$$p + \overline{p} \rightarrow t + \bar{t}$$

PARTICLE ACCELERATORS AND HIGH ENERGY PHYSICS

As it was said before, particle physics take care of the study of the elementary particles constituents of matter. It can be said, that these studies began with the discovery of electron in 1897 by J. J.Thomson [2, 3].

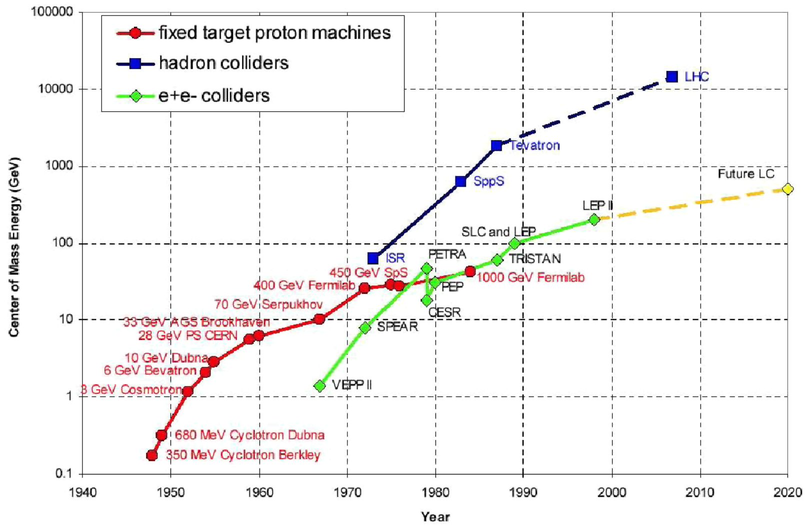

FIGURE 1. Development of High Energy Accelerators

Around 1930 and above, new particles were detected using Cosmic Rays as a source of energy, since it was the only high energy source known by then, starting with the discovery of the positron in 1931, and the muon in 1937[4]. The discovery of new particles was so many that the construction of High Energy Accelerators was impulsed, providing intense beams of known energy that lead us to discover the quark[5] substructure of matter.

One reason for what high energies became so important came from quantum mechanics, which describes particles as waves, whose wavelength is stablished by the de Broglie's expression: $\lambda = h/p$, being p, the beam momentum, and h the Planck's constans,which means that beams with higher momentums have shorter wavelengths, bringing higher resolutions, providing finer detail in the structure of fundamental particles.

Another important reason what high energy is needed for, remains in the fact that s there are many masive particle, requiring, acording to Einstein's equation $E = mc^2$, more energetic particles to produce them. The heaviest particle detected, the *top quark*[6, 7] (which has to be created as a pair with its antiparticle) has $mc^2 = 175$ GeV, which is almost 200 times the proton mass-energy.[8]

The Cyclotron:

In the 1930s, John D. Cockcroft and Ernest T. Walton built together the first accelerator to explore the nucleus, since in order to reach the high acceleration and energy needed for a charged particle to penetrate into the nucleous, a high voltage was needed, so they managed to construct an electric system that delivered $800kV$, which was used in the first proton accelerator. In 1932 they realised the first nuclear transformation initiated by a proton: $p + Li -> He + He$ [9, 10]. But there were problems with electric breakdowns that limited accelerating voltages to about a megavolt, this motivated Ernest

Lawrence to make up the principle of repeated acceleration, using a poweful magnetic field making the charged particle follow a circular orbit and forcing them to go through the accelerating field several times, increasing in this way the high voltage [11, 12]. This invention implied a new era in particle physics and the development of the accelerator techniques.

The first cyclotrons were built to ions accelerations, were classical mechanics still applies, so the balance between centripetal acceleration of motion in a circle, together with the magnetic field applied there can be expressed as:

$$evB = \frac{mv^2}{\rho},\ if\ v << c$$

where ρ is the circle radius.
this equation, can be rearranged:

$$B\rho = \frac{mv}{e},\ if\ v << c$$

obtaining then, the magnetic rigidity, the reluctance of the beam to be bent in a curve. This expression can be applied in the relativistic regime also, if we rewrite the expression mv by the relativistic momentum p

$$B\rho = \frac{p}{e}$$

And the radius of an orbit in a ciclotron is proportional to the revolution frequency and velocity

$$f = \frac{v}{2\pi\rho} = \frac{v}{2\pi}\frac{eB}{mv} = \frac{eB}{2\pi m}$$

This frequency remains constant as the particle is accelerated, an after that, a continuous stream of ions injected in the center follow an spiral path reaching their highest energy at the rim of the poles[13].

The Synchrotron:
Larger and larger accelerators have been built using Lawrence cyclotron invention. The bending magnets have grown large and heavy. Accelerators are now developed with several small bending magnets rather than one big magnet. To keep the orbit fixed, the magnetic field had to increase with increasing energy, so the magnetic field was synchronised with the increasing energy of the accelerated particles, giving origin to the synchrotron. The synchrotron varies the magnetic field intensity, which means particles don't move in a spiral but in a perfect circle.

Nowadays: To reach very high collision energies, many of the current accelerators are colliders in which two particles beams are accelerated in opposite directions for colisiong them. Doing this, almost all the particle energy can be employed for production

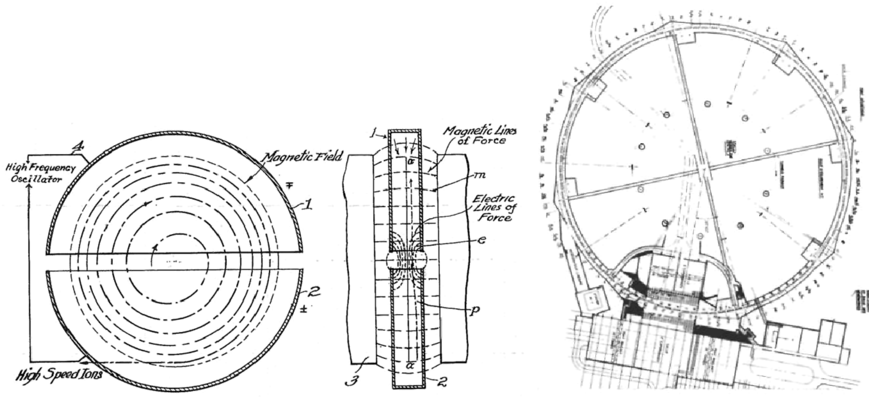

FIGURE 2. Left: Lawrence Cyclotron design. **Right:** The CERN 25GeV proton synchrotron

FIGURE 3. Tevatron and LHC Accelerators at Fermilab and CERN

of new particles, being able to obtain high collision energies to study the structure of matter.

The Energy needed for particles discovery is increasing more and more with time (see Fig. 1). Some examples for this type of detector are Tevatron at Fermilab, or the LHC at Cern (see Fig. 3.

Since 1939, the accelerators development has grown so much that the energy has improved from the $80keV$ from the original cyclotron of 13cm of diameter to the $10TeV$ from the LHC of 27 km of diameter.

UNSOLVED QUESTIONS

- Why the gravity is so weak?
- There exist extra-dimensions?
- What was the origin of our Universe?
- What is Dark matter?

- Is it our world supersymmetric?
- What is the nature of the neutrinos? They really have mass?
- There exist the Higgs boson?
- Waht is the Dark energy?

QUANTUM MECHANICS AND GRAVITY

Gravity as we currently understand it cannot be reconciled with the laws of quantum mechanics. Since 1930, people have tried to invent a theory of quantum gravity. Enrico Fermi was the first to propose a theory of quantum gravity, in 1931. However, Fermi's theory predicted that all forces were infinite, and therefore the universe could not exist. Most physicists think the universe does in fact exist, so it was thought that the theory of quantum gravity had some serious problems.

Shortly after quantum field theory was invented, people started trying to invent a quantum field theory of gravity. Very quickly, it was shown that this is impossible: there can be no theory of gravity which obeys the rules of quantum field theory. The quantum theory of fields simply will not work for a force with the properties of gravity. It was recognized that a completely new type of theory was required. Since this theory does not currently exist, no one is certain exactly what it looks like. However, most people presume we need a new theory of space and time which will be compatible with the laws of quantum mechanics as we know them, and somehow allow a theory of quantum gravity to exist. This new theory of space and time is often called Quantum Relativity (see Figure 4).

STRING THEORY

An extremely popular though somewhat controversial line of research which has captivated a sizeable proportion of the theoretical community is that of String Theory. Whilst well beyond the scope of this course, a few words are appropriate. String theory is a candidate for a quantum theory of gravity. Elementary particles are viewed as excitations of basic strings, as in the cartoon in Figure 5. Rather than a particle being viewed as a point tracing out a world-line in space-time, it is thought of as a string, possibly closed into a loop, tracing out a two-dimensional world-sheet in space-time. The addition of supersymmetry to the concept of strings leads to Superstring theory.

The controversy arises from the criticism that string theory does not make predictions testable by experiment. Recent developments have softened that criticism. The natural size of strings was thought to be related to the Planck mass scale $\sim$ 1019 GeV. This would imply that strings have average length scales of $\sim$ 1035 m. Note that we can only probe distance scales down to $\sim$ 1018 m using present-day accelerators. It is this discrepancy of scales that makes it difficult for experiment. Strings would just be toot small. However there is now a line of thought that the fundamental string scale may be of order $\times$1018 m to $\times$1019 m, that is, the string scale does not have to be related

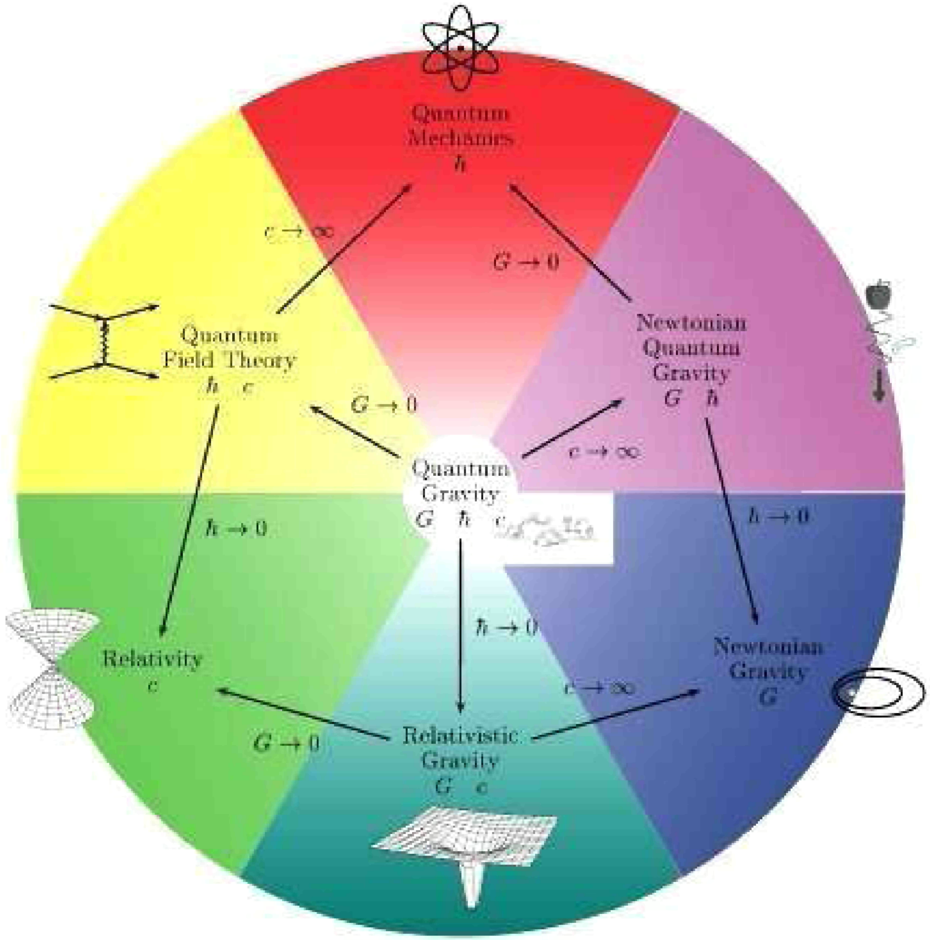

FIGURE 4. The relationship between quantum gravity and the other branches of physics at the limit of the various universal constants, where the gravitational constant G is associated with gravity, the Planck constant $\hbar$ is for quantum, and the velocity of light c comes with special relativity. In quantum gravity, all the fundamental units are expressed in terms of G, $\hbar$ and c: Planck length $= (G\hbar/c^3)^{1/2} = 1.62 \times 10^{-33}$ cm, Planck time $= (G\hbar/c^5)^{1/2} = 5.39 \times 10^{-44}$ s, Planck mass $= (\hbar c/G)^{1/2} = 2.17 \times 10^{-5}$ g, Planck energy $= (\hbar c^5/G)^{1/2} = 1.22 \times 10^{19}$ Gev, and Planck temperature $= (\hbar c^5/G k_B{}^2)^{1/2} = 1.42 \times 10^{32}$ K, where k_B is the Boltzmann's constant, which relates energy to absolute temperature on the Kelvin scale.

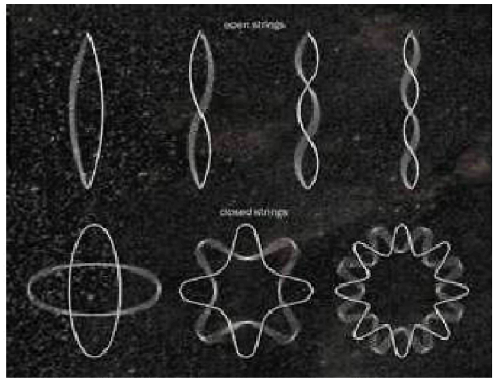

FIGURE 5. The possible nature of strings. Diagram taken from reference [14]

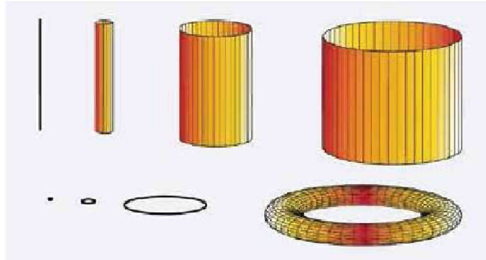

FIGURE 6. Strings of different sizes. Diagram taken from reference [14].

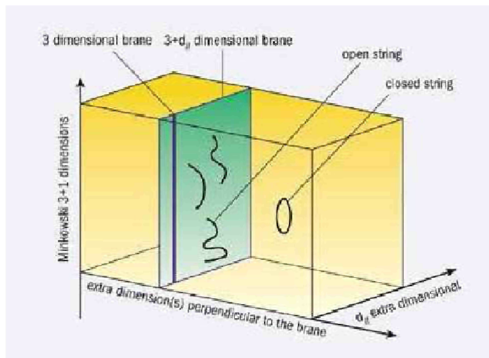

FIGURE 7. A schematic representation of branes. Diagram taken from reference [14].

to the Planck scale. This would make the natural energy scale in the TeV region. and potentially accessible to the LHC experiments.

Extra Dimensions

String theory predicts the existence of six new spatial dimensions. These may be compactified and inaccessible to observation at present. The concept of the presence of unobserved extra dimensions is illustrated rather loosely in Figure 6, where an object with cylindrical or toroidal structure could for example appear as lines or points if the extra dimensions are too small to be resolved.

The concept of branes has to do with the idea that whilst there may be extra dimensions to the three spatial and one time dimension with which we are familiar, not all of the interactions propagate in all of the extra dimensions. This is illustrated in Figure 7.

The p-branes generalize the concept of point particles to higher dimensional objects extended in p spatial dimensions. So we have

p = 0, point particles

p = 1, strings

The extra dimensions introduced by string theory are broken into those parallel to the brane and those perpendicular. Light, or more generally the force carriers of Standard Model interactions, are described by open strings propagating on the 3 + d dimensional brane. Gravity is described by closed strings and can propagate in the extra perpendicular dimensions.

Over the development of the subject there have been several different versions of string theory. Nowadays there is talk of M-theory, Mother of all theories, defined in 11 spatial dimensions, of which the various forms of string theory are approximations. Note that one should be reminded that there is currently no experimental evidence for strings.

THE BIG BANG THEORY

The Big Bang theory is an effort to explain what happened at the very beginning of our universe. Discoveries in astronomy and physics have shown beyond a reasonable doubt that our universe did in fact have a beginning. Prior to that moment there was nothing; during and after that moment there was something: our universe. The big bang theory is an effort to explain what happened during and after that moment.

According to the standard theory, our universe sprang into existence as "singularity" around 13.7 billion years ago. What is a "singularity" and where does it come from? Well, to be honest, we don't know for sure. Singularities are zones which defy our current understanding of physics. They are thought to exist at the core of "black holes." Black holes are areas of intense gravitational pressure. The pressure is thought to be so intense that finite matter is actually squished into infinite density (a mathematical concept which truly boggles the mind). These zones of infinite density are called "singularities." Our universe is thought to have begun as an infinitesimally small, infinitely hot, infinitely dense, something - a singularity.

After its initial appearance, it apparently inflated (the "Big Bang"), expanded and cooled, going from very, very small and very, very hot, to the size and temperature of our current universe. It continues to expand and cool to this day and we are inside of it: incredible creatures living on a unique planet, circling a beautiful star clustered together with several hundred billion other stars in a galaxy soaring through the cosmos, all of which is inside of an expanding universe that began as an infinitesimal singularity which appeared out of nowhere for reasons unknown.

Big Bang cosmology implies a certain predictable course for the thermal history of the universe. In the figure 8 we can see that history, emphasizing the two classic pieces of evidence that support it: the relative abundances of the light elements produced by primordial nucleosynthesis and the existence, spectrum, and fantastic isotropy of the cosmic microwave background.

Figure 8 outlines the calendar of events, or major epochs, in the history. It can be divided into two main periods: the radiation-dominated period, which lasted for approximately ten thousand years (1011 seconds), and the matter-dominated period from ten thousand years after the Big Bang to the present. During the ïňĄrst fraction of a second after the Big Bang, the constituents of the universe undoubtedly included the particles of the standard model of particle physics: leptons, quarks, and the gauge bosons that mediate interactions among them, all moving at velocities so close to the velocity of light that from the point of view of thermodynamics, they behaved as particles of

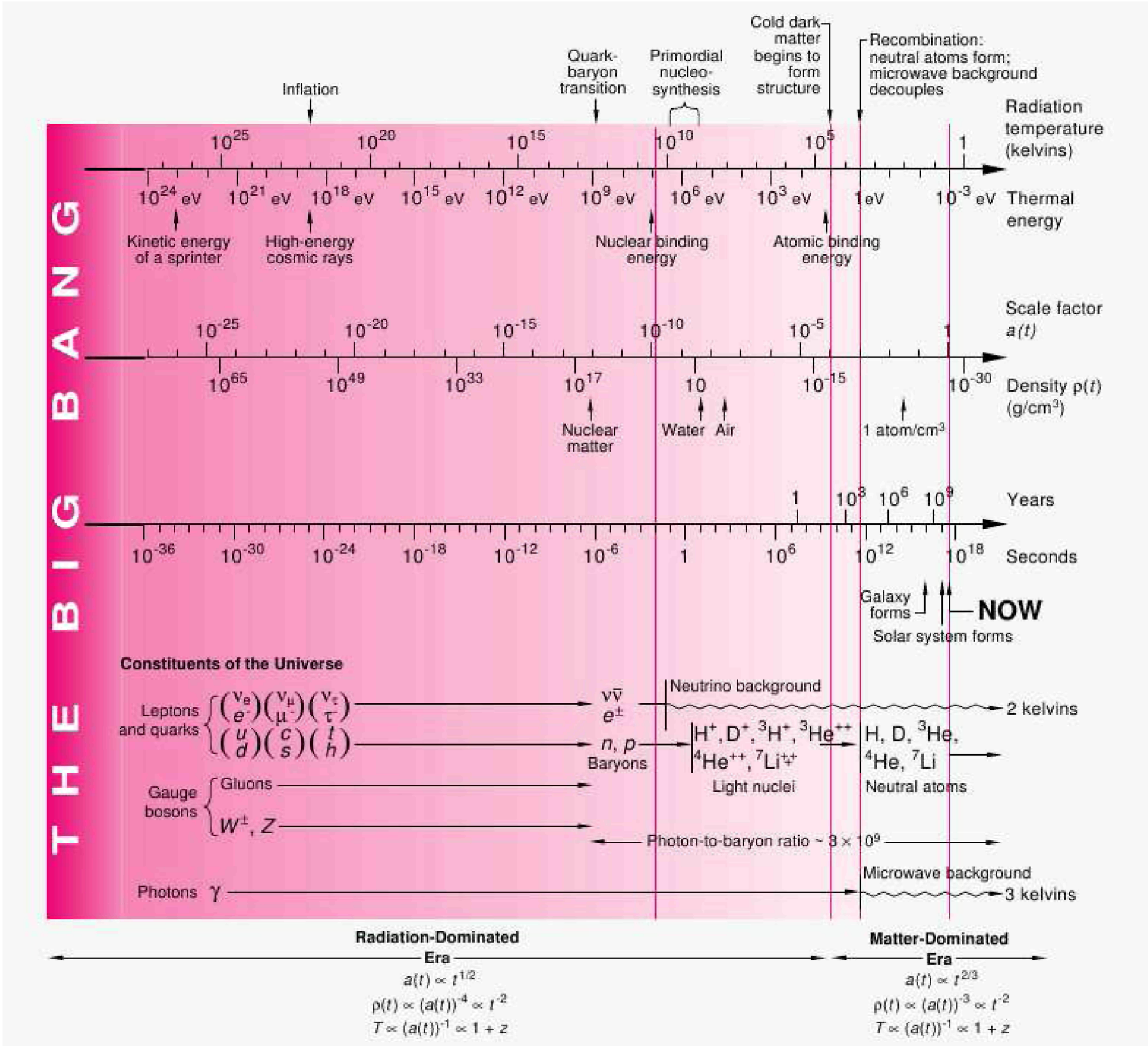

FIGURE 8. The thermal history of the universe, The figure 8 shows important epochs in the history of the universe according to standard Big Bang cosmology. It also shows the particles of matter and radiation constituting the universe during each epoch.

radiation (that is, massless particles). The physics during this time is highly speculative. It is assumed that thermal energies were initially at the Planck scale (1028 eV), where the exotic and poorly understood phenomenon of quantum gravity could have played a crucial role. Many particle physicists and astrophysicists believe that a bit later, as the temperature cooled to 1026 kelvins, there was a brief period of inflation. During the inflationary phase, the size of the universe grew exponentially by a factor of at least 1028. Less speculative is the prediction that at a temperature around 1012 kelvins, a quark-hadron transition occurred, when all the quarks and gluons combined to form protons and neutrons. The particles of cold dark matter, if they exist, would also have been created sometime after the inflationary phase.

DARK MATTER

The existence of Dark (i.e., non-luminous and non-absorbing) Matter (DM) is by now well established. The earliest [15], and perhaps still most convincing, evidence for DM came from the observation that various luminous objects (stars, gas clouds, globular clusters, or entire galaxies) move faster than one would expect if they only felt the gravitational attraction of other visible objects. An important example is the measurement of galactic rotation curves. The rotational velocity v of an object on a stable Keplerian orbit with radius r around a galaxy scales like $v(r) \propto \sqrt{M(r)/r}$, where $M(r)$ is the mass inside the orbit. If r lies outside the visible part of the galaxy and mass tracks light, one would expect $v(r) \propto 1/\sqrt{r}$. Instead, in most galaxies one finds that v becomes approximately constant out to the largest values of r where the rotation curve can be measured; in our own galaxy, $v \simeq 220$ km/s at the location of our solar system, with little change out to the largest observable radius. This implies the existence of a dark halo, with mass density $\rho(r) \propto 1/r^2$, i.e., $M(r) \propto r$; at some point ρ will have to fall off faster (in order to keep the total mass of the galaxy finite), but we do not know at what radius this will happen. This leads to a lower bound on the DM mass density, $\Omega_{DM} \geq 0.1$, where $\Omega_X \equiv \rho_X/\rho_{crit}$, ρ_{crit} being the critical mass density (i.e., $\Omega_{tot} = 1$ corresponds to a flat Universe).

The observation of clusters of galaxies tends to give somewhat larger values, $\Omega_{DM} \simeq$ 0.2 to 0.3. These observations include measurements of the peculiar velocities of galaxies in the cluster, which are a measure of their potential energy if the cluster is virialized; measurements of the X-ray temperature of hot gas in the cluster, which again correlates with the gravitational potential felt by the gas; and most directly studies of (weak) gravitational lensing of background galaxies on the cluster. The currently most accurate, if somewhat indirect, determination of Ω_{DM} comes from global fits of cosmological parameters to a variety of observations. For example, using measurements of the anisotropy of the cosmic microwave background (CMB) and of the spatial distribution of galaxies, we can find a density of cold, non - baryonic matter.

$$\Omega_{nbm}\hbar^2 = 0.111 \pm 0.006 \tag{1}$$

where $\hbar$ is the Hubble constant in units of 100 km/(s.Mpc). Some part of the baryonic matter density

$$\Omega_b\hbar^2 = 0.023 \pm 0.001 \tag{2}$$

may well contribute to (baryonic) DM, e.g., MACHOs [16] or cold molecular gas clouds [17]. The DM density in the “neighborhood” of our solar system is also of considerable interest. This was first estimated as early as 1922 by J.H. Jeans, who analyzed the motion of nearby stars transverse to the galactic plane [15]. He concluded that in our galactic neighborhood the average density of DM must be roughly equal to that of luminous matter (stars, gas, dust). Remarkably enough, the most recent estimates,

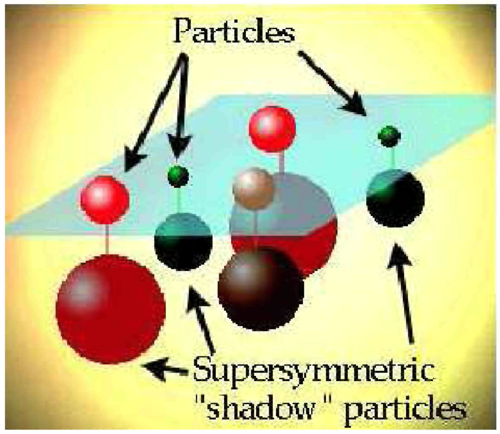

FIGURE 9. Each known fundamental particle has a superpartner.

based on a detailed model of our galaxy, find quite similar results [18]:

$$\rho_{DM}^{local} \simeq 0.3 \frac{GeV}{cm^3} \tag{3}$$

this value is known to within a factor of two or so. Numerous new experiments are in line to bring accurate measurements to constrain or discover Dark Matter.

SUPERSYMMETRY

Supersymmetry is a proposed theory which relates fermions to bosons. Even though there is no experimental evidence whatsoever for any supersymmetric particles, supersymmetry remains popular because it provides potential solutions to several problems in particle physics. The basic idea of supersymmetry is that each elementary fermion has a corresponding supersymmetric boson partner, and each elementary boson has a corresponding supersymmetric fermion partner. The supersymmetric partners must be heavier than their known particle partners since they have not been observed to date. Thus supersymmetry must be a broken symmetry. The concept of supersymmetry is illustrated in Figure 9. Note that pictures such as this one are a little misleading. The supersymmetric partners are drawn as larger spheres to indicate that the particles have a larger mass. Do not confuse this with the idea that the particles are larger in physical extent. In our theories the fundamental fermions and bosons (and their superpartners) are all point-like.

Particles and Sparticles

The supersymmetric partners of the Standard Model particles are given the generic name sparticles. Examples are given in Table 2. Since fermions are half-integral spin and bosons integral spin, the supersymmetric partners of fermions are integral spin and those of bosons half-integral spin. A supersymmetric partner of a given particle will differ from the partner by a half unit of spin.

TABLE 2. Selected particles and sparticles

Particle	Spin	Sparticle	Spin
Quark	1/2	Squark	0
Lepton	1/2	Slepton	0
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
W Boson	1	Wino	1/2
Z Boson	1	Zino	1/2
Higgs Boson	0	Higgsino	1/2

TABLE 3. Parameters of the Standard Model

The masses of the six quarks	6
The masses of the three charged leptons	3
The coupling constants of SU(3), SU(2) and U(1)	3
The Higgs mass and vacuum expectation value	2
The CKM matrix angles and complex phase	4
The QCD phase θ	1
	19

All supersymmetric theories predict more Higgs bosons than the single scalar particle accompanying the Standard Model. In the simplest supersymmetic extension to the Standard Model, the number of Higgs bosons increases to five. The lightest supersymmetric particle is expected to be stable, due to a symmetry known as R-parity. As such it is a natural dark matter candidate. Despite addressing problems with the Standard Model in an elegant and satisfying way, supersymmetry nevertheless comes at a cost. The number of parameters in even the minimal supersymmetric extension of the Standard Model rises dramatically from the 19 that are listed at the table 3. If supersymmetric particles are indeed observed at the next generation of colliders, this will not be the end of the questions or the search for a truly satisfying theory.

NEUTRINOS

This section is reviewed in the lectures of Edgar Casimiro and Lino Miramonti, in this proceedings.

HIGGS FIELD AND DARK ENERGY

From the point of view of cosmology, the vacuum appears to have an energy density, which is sometimes called “dark energy” or the “cosmological constant”, responsible for the observed accelerated expansion of the universe. From a particle physics viewpoint, the vacuum is permeated by a “Higgs Field” - named after physicist Peter Higgs [19]. In the Standard Model of particle physics (which has mapped the subatomic world with remarkable success for over 30 years), the masses of all particles are generated as a

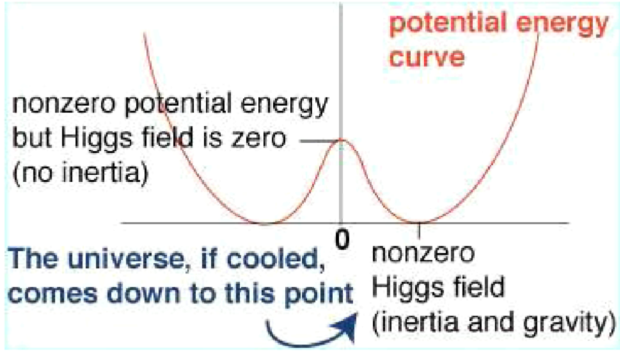

FIGURE 10. The formation of the nonzero Higgs field is (when the universe cools down) nothing but a phase transition of the universe: the transition which produces gravitational force (gravitational and inertial mass are the same). We can see, the manner of such a phase transition in this figure; imagine a ball, initially located at the top of the center hill rolls down the curve, and it will come to rest somewhere in the bottom. Also, the inflationary burst (the Higgs field is called inflaton field there) of the early universe is essentially related with this phrase transition,

result of their interactions with this field.

Then, Higgs field is the mechanism by which particles gain mass, it should also be possible to detect excitations of the Higgs field in the form of a particle known as the “Higgs boson”, the Higgs boson can be seen as a dense point in the field, in Standard Model Higgs bosons are electrically neutral (some extensions to SM predict charged Higgs). Detecting the Higgs - the only particle in the Standard Model that has not been observed experimentally - is therefore one of the outstanding challenges in particle physics today. Scientists hope to detect the Higgs using CERN’s Large Hadron Collider (LHC), due to come online in November this year. The LHC will be the world’s largest particle accelerator, colliding protons on protons at a total energy of 16 TeV (16×10^{12} eV) to generate what physicists hope will be a slew of new particles, including the Higgs.

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