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Unification of Gravity and Quantum Theory

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Abstract- An overview of the four fundamental forces of physics as described by the Standard Model (SM) and prevalent unifying theories beyond it is provided. Background knowledge of the particles governing the fundamental forces is provided, as it will be useful in understanding the way in which the unification efforts of particle physics has evolved, either from the SM, or apart from it. It is shown that efforts to provide a quantum theory of gravity have allowed supersymmetry (SUSY) and M-Theory to become two of the prevailing theories for unifying gravity with the remaining non-gravitational forces.

I. INTRODUCTION

The force of gravity was the first of the four fundamental forces of physics force to be recognized, and likely the most familiar to people today. It's the force that holds the universe as we know it together. It may come as a surprise then that the strength of gravity is weaker by over thirty orders of magnitude relative to the three non-gravitational fundamental forces. The weakness of gravity is a key reason that it is also the least understood force in terms of its quantum behavior. Understanding the behavior of gravity at the quantum scale is necessary for a unified theory covering all four fundamental forces, called a Theory of Everything (TOE). This paper attempts to provide a description of the difficulties associated with understanding gravity's quantum behavior and how that affects our current attempts at unifying the fundamental forces.

A unified theory of the fundamental forces simply means that a single theory can provide the equations and physical description of every interaction, which would ultimately become the so-called TOE. A TOE is a term for the ultimate theory of the universe—a set of equations and principals capable of describing all phenomena that have ever occurred or will ever be observed [1]. While there is no guarantee that the forces are even unifiable, scientists have many reasons to believe that they could be, and have made significant progress in their attempts both recently and historically.

II. BRIEF HISTORY OF UNIFICATION THEORIES

While unification has long been a goal of science, the first modern step forward was taken in the late 1600s when Sir Isaac Newton revealed the deep connection between the steady pace of celestial bodies moving across space and the pace of objects falling on earth. Newton's insight was that the force that governs matter here on Earth was the same force governing the matter in space. Another critical step forward in unification was accomplished in the 1860s when James C. Maxwell wrote down his famous Maxwell's Equations, showing that electricity and magnetism were just two facets of a more fundamental phenomenon he called electromagnetism. Again, in the 1960s, physicists demonstrated that electromagnetism and another fundamental force, the weak nuclear force, were part of a single phenomenon they called the electroweak force. More recently, scientists have predicted the unification of the strong force with the electroweak force in grand unified theories. Grand unified theories of the non-gravitational forces are possible because unlike gravity, they are well understood at the quantum scale. Despite this, scientists still have reasons to believe that the seemingly independent remaining force of gravity is unifiable.

III. QUANTUM GRAVITY AND THE STANDARD MODEL

Unifying gravity with the other forces has been so far unsuccessful because Albert Einstein's famous description of gravity, the theory of general relativity (GR) [2], breaks down in the quantum realm of subatomic particles. Conversely, the non-gravitational forces, specifically electromagnetism, and the strong and weak nuclear forces are all fully described at the quantum scale by theories which fall under a common framework called the SM of particle physics, or just SM. The SM is one of physics most successful theories, providing the mathematical and physical description of matter and the non-gravitational forces at the quantum scale as the motion and interactions of subatomic, elementary particles. Albert Einstein spent much of his later life attempting to reconcile his general relativistic theory of gravity's macroscopic phenomena to account for its quantum effects in the microscopic realm, shown in one of his publications [3]. A theory of gravity under the SM necessitates a theory for quantum gravity, which predicts that the force of gravity would be carried by elementary force particles interacting with matter particles. To further understand this concept, a general overview of the fundamental forces and elementary particles under the SM is provided to review our current understanding of the nature of reality.

IV. FUNDAMENTAL FORCES AND PARTICLES

This section will provide the answers to the questions of what are the fundamental building blocks of reality, and what are the rules that govern them? Appendix I provides a visual breakdown of the topics that will be discussed.

A. Fundamental Forces

By now, we are familiar with the force of gravity, and perhaps electromagnetism, which is the source of light, electricity, magnetism, and all chemical reactions. There are also the two nuclear forces called the weak nuclear, responsible for radioactive decay and nuclear fusion, and the strong nuclear, which binds together the protons in atomic nuclei as well as the quarks which make up the protons.

The forces possess measurable qualities, shown below in decreasing order of relative strength:

TABLE 1
MEASURABLE QUALITIES OF THE FORCES

Force	**Strength**	**Range(cm)**	**Charge neutrality**
Strong Nuclear	10	10^{-13}	Yes
Electro-magnetic	10^{-2}	∞	Yes
Weak Nuclear	10^{-5}	10^{-15}	Yes
Gravitational	10^{-36}	∞	No

Although the strong and weak forces are much stronger than gravity, their range is limited. Beyond the size of approximately a proton, the nuclear forces essentially do not exist and the only forces we can feel in the macroscopic world which we experience are the electromagnetic and gravitational due to their infinite range. Gravity is the only force that is not charge neutral, meaning there is no opposing force to gravity. So, although gravity is weaker than the other forces by more than 30 orders of magnitude [4], it becomes the dominant force over cosmic distances due to the neutral electromagnetic charge of celestial bodies and the limited range of the nuclear forces.

On the most fundamental level, the SM asserts that the forces are simply the interactions between elementary matter particles. Elementary matter particles interact with each other indirectly through the exchange of force particles, which cause them to attract or repel each other, or change them from one type of matter particle to another. This exchange of force particles between matter particles is the fundamental action resulting in the fundamental forces we know today.

B. Elementary Particles

An elementary particle is defined as one of the point-like constituents of matter or force with no known substructure. All known elementary particles are categorized in the SM, analogous to how the periodic table categorizes the elements. The SM divides all known elementary particles and their properties into two classifications of either matter particles or force particles, named fermions and bosons, respectively.

1) Fermions

Most are familiar with atoms, consisting of a proton and neutron nucleus, along with the electron that orbits the nucleus. While these are all considered atomic particles, only the electron is an elementary particle. Specifically, the electron is one of two types of fermions, called leptons, whereas the proton and neutron are composite particles, or hadrons, further made up of a different type of fermion, called quarks. Fermions are characterized by their spin, and are further divided into leptons and quarks. There are six classified types of leptons: electron, muon, tau, electron neutrino, muon neutrino, and tau neutrino, and 6 types, or flavors, of quarks: up, down, charm, strange, top, and bottom. The different variations of leptons and quarks make up all the matter in the universe. For example, depending on the combination of quark flavors, three quarks will form either a neutron or proton.

2) Bosons

The quarks making up protons and neutrons are physically held together by a boson associated with the strong force called a gluon. Without bosons, matter particles would never condense to form atoms. Each force is carried by specific bosons. We are now familiar with the gluon boson, which carries the strong force. The electromagnetic force is carried by the familiar boson called a photon, and the W and Z bosons are responsible for the weak force.

The properties of all the different types of fermion and boson particles are classified in the SM and have been extensively confirmed in particle collider experiments. Because of the accuracy of the SM to describe all the forces other than gravity, scientists naturally assume that there should also be a boson that carries the force of gravity. This hypothetical boson has already been given the name graviton, but attempts at including it under the SM have been so far unsuccessful.

V. GRAVITONS AND THE STANDARD MODEL

Attempts to include gravitons in the SM have been unsuccessful due to predicted properties that the graviton would possess, if they exist. As an effective field theory, the SM relies heavily on a mathematical process called renormalization to describe the interactions of the elementary particles. The topic of renormalization is beyond the scope of this paper, but more information may be found here [5]. Plainly explained, because gravity is not a charge neutral force, the process of renormalization cannot be applied to gravitons, unlike the other bosons.

SM requires that bosons possess a strength at a level well above the plank scale, which is the smallest unit of measurement. Due to the relative weakness of gravity, it dictates the graviton’s strength could only exist at the plank scale.

These are only some examples of shortcomings SM possesses as it relates to gravity, but there are even more significant shortcoming beyond the scope of this article relating to dark matter and neutrino masses. So, while the SM is one of physics most successful theories, the fact that it says absolutely nothing about the force of gravity, and its other inadequacies have prompted the emergence of theories beyond the SM (TBSM).

VI. THEORIES BEYOND THE STANDARD MODEL

A TOE would provide the mathematical framework capable of describing all elementary particles making up reality as we know it. Ideally, the theory would also be able to accurately predict all the properties that subatomic particles possess such as their charge, spin, mass or strength. This is not the case for the SM, as the properties of the particles it contains have been largely accepted solely based on the experimental results obtained, rather than explained and more importantly, predicted by it. Attempts at addressing the shortcomings of the SM have led to TBSM such as supersymmetric (SUSY) models [6, 7], and subsequently superstring theories. These new models have either expanded upon the SM, or redefined a completely new model of particle physics.

A. Supersymmetry

SUSY is an extension of the SM. To be clear, SUSY is not a theory, but a principle that a theory could have. Any theory that treats forces and matter on equal footing are said to have SUSY, thus there are many different SUSY theories. As counter intuitive as it sounds that matter and force particles could be equal, SUSY provides an elegant solution to many of the mysteries that the SM has no answers for.

SUSY in a single sentence, is a theory in which the equations used in the SM for force and the equations for matter are identical. By treating matter and force particles identically, SUSY theories predict that each particle in the SM also has a partner particle, called a sparticle, effectively doubling the amount of elementary particles predicted to exist. Although the existence of sparticles has never been observed in any experiments, SUSY is an enticing concept. It turns out that equations that contain SUSY can explain why the force of gravity is so weak, and could also lead to the unification of the forces at a fixed energy, providing the basis of grand unified theories (GUTs) and TOEs.

B. String Theory

SM and SUSY theories dictate that the most fundamental building blocks of reality are matter and force particles, fermions and bosons. String theory is different concept that asserts that even fermions and bosons are further made up of an even more fundamental, continuously vibrating particle, called a string. String particles if they were to exist, would be so miniscule in size that their existence will likely never be proven. Despite this, the theory is perhaps the most promising example of a candidate for a TOE.

The concept of string theory is that every subatomic particle can be created by a single vibrating string like filament. Similar to the way musical instruments produce different tones depending on the vibrating frequency of its strings, all the particles in existence along with their associated properties are determined by how its internal string vibrates. This elegant theory depicts the universe arising from a symphony of vibrating strings, with each note creating a particle of force or matter.

Early string theories were abandoned, but eventually were superseded by superstring theories that incorporate the principles of SUSY. Five separate superstring theories eventually emerged incorporating numerous dimensions in attempts to describe the many subatomic particles using strings. The five superstring theories were eventually united by Edward Witten into an eleven-dimensional theory called M-Theory [8].

VII. UNIFICATION THEORIES

A. Supersymmetric Unification

A unification of the forces would imply that the strengths of the forces are actually equal. By applying renormalization techniques to data extrapolated from high energy particle accelerators, it has been predicted that at a certain high energy level, known as unification energy, the bosons of different forces are coupled, essentially making them indistinguishable from each other in terms of their strengths.

To observe elementary particles, high energy particle accelerators are necessary. The highest energy obtainable by the particle accelerator is proportional to the smallest scale at which particles may be observed. Physicists have found that the coupling strengths of the non-gravitational forces vary as a function of the energy, or scale at which they are studied. Extrapolating the data to energy levels beyond what is experimentally possible using SM equations shows the coupling strength of the non-gravitational forces become very similar but do not completely converge. However, when extrapolated using SUSY equations, the coupling strengths of the bosons converge to a fixed energy level, providing a GUT. Furthermore, because SUSY can predict the effect of forces well beyond scales achievable by the SM, some SUSY theories even predict the unification of gravity with the GUT force on the plank scale at 19 GeV.

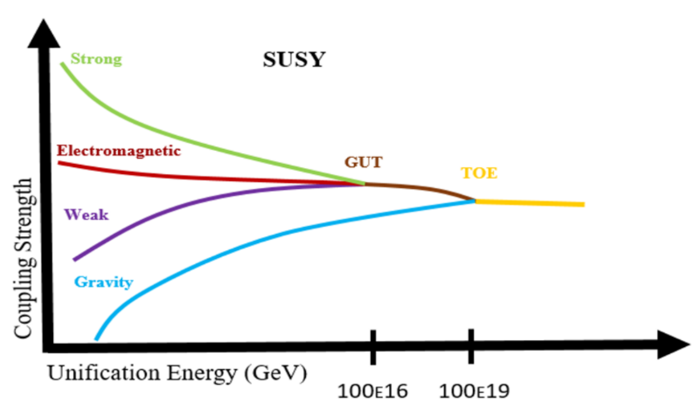

Fig 2: Coupling Strengths using SUSY Converge

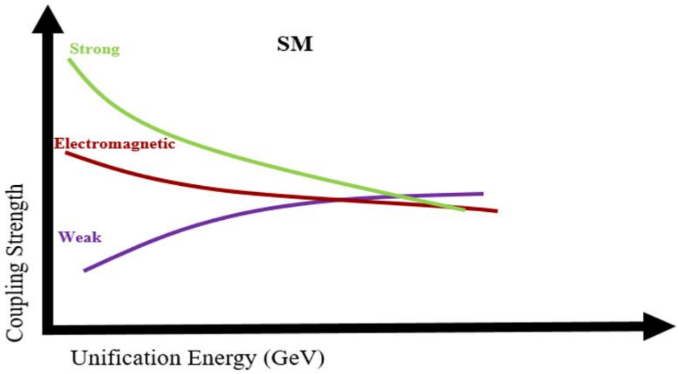

Fig 3: Coupling Strengths using the SM do not converge

SUSY indeed provides elegant results and has thousands of publications supporting its principles, but it is still a theory without any proof. The search for the existence of the sparticles required by this model continues.

B. String Theory Unification

String theories, such as M-Theory, are attractive as a model for TOE's because they are the only theories capable of describing the quantum effects of all four forces to include quantum gravity. M-Theory's ability to describe gravity is the main reason for its conception, as the existence of a particle that has the properties consistent with a graviton arises from its equations. Further solutions of the equations of the vibrating string in M-Theory have even predicted the existence and properties of all the boson associated with the other forces that have already been experimentally confirmed.

The simplicity of the physical concept of vibrating strings does not translate to a simple mathematical structure required to accommodate this theory. For strings to exist with the ability to produce every particle known, the theory requires that they vibrate in seven dimensions, adding to the three spatial and one time dimension, for a total of eleven dimensions required for M-Theory. Extra dimensions, as well as supersymmetric particles have never been experimentally proven, and may never be due to the technological limitations. Without such proof, string theory may likely remain just a beautiful idea.

VIII. CONCLUSION

We have learned that the laws of physics as we know them are not consistent since we cannot describe gravity in the quantum realm. Formulating a correct theory of quantum gravity would provide a way to create a TOE. String theory is a viable theory beyond the SM that enables us to study phenomena that we expect in a theory of quantum gravity. The theory is not yet developed to the point of making definite experimental predictions, but it is understood well enough to explain some quantum gravity phenomena. Supersymmetric phases of string theory are well explored but experimentally unconfirmed. It is possible that in the future we will understand these theories better so that they may be experimentally observed.

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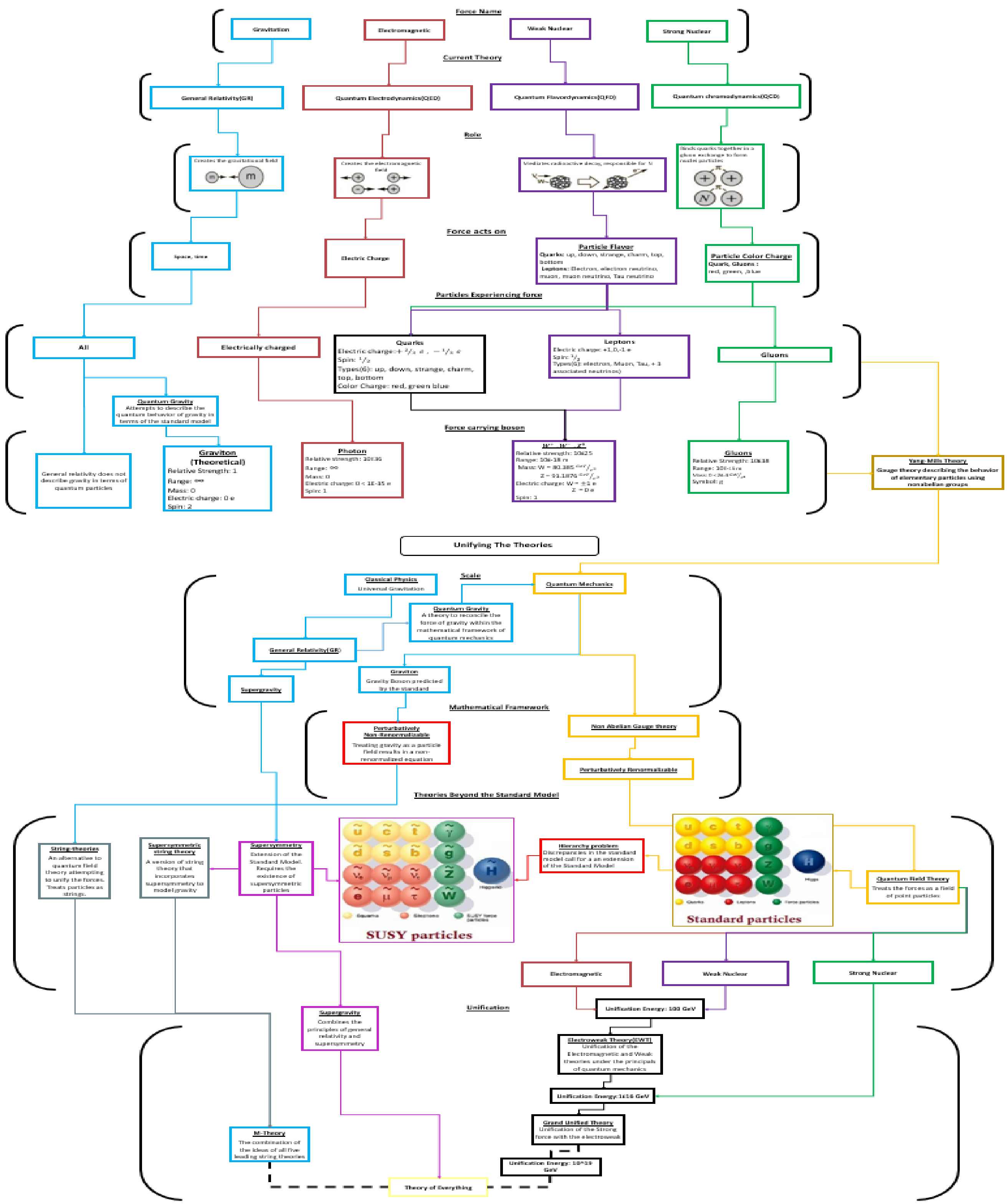
APPENDIX



Force Name
Gravitation
Electromagnetic
Weak Nuclear
Strong Nuclear
Current Theory
General Relativity(GR)
Quantum Electrodynamics(QED)
Quantum Flavordynamics(QFD)
Quantum chromodynamics(QCD)
Role
Creates the gravitational field
Creates the electromagnetic field
Mediates radioactive decay, responsible for
Binds quarks together in a gluon exchange to form nuclei particles
Force acts on
Space, time
Electric Charge
Particle Flavor
Quarks: up, down, strange, charm, top, bottom
Leptons: Electron, electron neutrino, muon, muon neutrino, Tau neutrino
Particle Color Charge
Quark, Gluons :
red, green, ,blue
Particles Experiencing force
All
Electrically charged
Quarks
Electric charge:+ 2/3 e , − 1/3 e
Spin: 1/2
Types(6): up, down, strange, charm, top, bottom
Color Charge: red, green blue
Leptons
Electric charge: +1,0,-1 e
Spin: 1/2
Types(6): electron, Muon, Tau, + 3 associated neutrinos)
Gluons
Quantum Gravity
Attempts to describe the quantum behavior of gravity in terms of the standard model
Force carrying boson
General relativity does not describe gravity in terms of quantum particles
Graviton
(Theoretical)
Relative Strength: 1
Range: ∞
Mass: 0
Electric charge: 0 e
Spin: 2
Photon
Range: ∞
Mass: 0
Spin: 1
Gluons
Yang-Mills Theory
Gauge theory describing the behavior of elementary particles using nonabelian groups
Unifying The Theories
Scale
Classical Physics
Universal Gravitation
Quantum Mechanics
Quantum Gravity
A theory to reconcile the force of gravity within the mathematical framework of quantum mechanics
General Relativity(GR)
Supergravity
Graviton
Gravity Boson predicted by the standard
Mathematical Framework
Perturbatively Non-Renormalizable
Treating gravity as a particle field results in a non-renormalized equation
Non Abelian Gauge theory
Perturbatively Renormalizable
Theories Beyond the Standard Model
String-theories
An alternative to quantum field theory attempting to unify the forces. Treats particles as strings.
Supersymmetric string theory
A version of string theory that incorporates supersymmetry to model gravity
Supersymmetry
Extension of the Standard Model. Requires the existence of supersymmetric particles
SUSY particles
Hierarchy problem
Discrepancies in the standard model call for a an extension of the Standard Model
Standard particles
Quantum Field Theory
Treats the forces as a field of point particles
Electromagnetic
Weak Nuclear
Strong Nuclear
Unification
Unification Energy: 100 GeV
Supergravity
Combines the principles of general relativity and supersymmetry
Electroweak Theory(EWT)
Unification of the Electromagnetic and Weak theories under the principals of quantum mechanics
Grand Unified Theory
Unification of the Strong force with the electroweak
M-Theory
The combination of the ideas of all five leading string theories
Theory of Everything