String Theory predictions that relate to exotic dark matter

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String theory is the most prominent theory of everything, one that unifies all of our knowledge and understanding of the physics universe. Understanding Dark Matter is an outstanding unsolved problem that challenges the very fundamentals of our knowledge of the universe. Most physicists would agree with the fact that dark matter requires physics well beyond our current capabilities and comfort. Thus it only makes sense that within the theory of everything lies clues to the problem that seems impossible to understand. This paper aims to collate knowledge from different places and draw a relation between the two topics in turn helping people in the future who aim to do the same.

Introduction

History of String Theory

String theory is a theoretical framework that attempts to reconcile two individually mathematically elegant theories: ”Quantum Mechanics” and ”General Relativity.” The main idea it puts forth is that the universe is made up of tiny one-dimensional strings rather than point-like particles. These strings oscillate at varying frequencies to create the particles that we observe. The origins of String Theory can be traced back to the 1960s[1] when physicists were trying to understand and evaluate the strong nuclear force that holds the atomic nuclei together. The discovery of Quarks and the development of Quantum Chromodynamics only really provided a partial solution. However, a lot of questions remained unanswered. Gabriele Veneziano was researching the strong nuclear force, which holds atomic nuclei together, in 1968. At the time, scientists were having difficulty comprehending the scattering amplitudes (probabilities of particles scattering off one another) of hadrons, which are strongly interacting particles. The Euler beta function, which may be found in mathematical equations relating to particle scattering in quantum field theory, served as a model for Veneziano. Veneziano postulated that a mathematical formula called the scattering amplitude formula may be used to characterise the scattering amplitudes of hadrons. The Euler beta function, which shared some of the same mathematical characteristics as what he was attempting to express, served as the basis for the formula he created. The function is given below:

$$B(z_1,z_2)=\int_0^1 t^{z_1-1}(1-t)^{z_2-1}dt \tag{1}$$

The characteristics of the scattering amplitudes seen experimentally were effectively reconstructed by Veneziano’s formula, now known as the Veneziano amplitude. It was a noteworthy accomplishment that offered a fresh perspective on the strong nuclear force.The importance of Veneziano’s work in the context of string theory was discovered much later. Early in the 1970s, physicists developed a theoretical framework called dual resonance models with the goal of employing strings as fundamental objects to explain the observed features of hadrons. It was discovered that the Veneziano amplitude was a particular instance of the more comprehensive framework known as string amplitudes, which defined the scattering of strings. The realisation that the strings in the dual resonance models were more than just a mathematical tool with important physical ramifications came about as a result of these discoveries. Modern string theory, which contends that fundamental particles are small vibrating strings rather than point-like entities, is based on this realisation. Although this theory was a pillar for the foundation of string theory, it remained incomplete because it did not incorporate gravity.

In the 1970s, his theory was further developed by physicists John Schwarz, Michael Green, and Edward Witten[1]. They showed that their modified version of string theory could explain the strong nuclear force and simultaneously incorporate all the fundamental forces of nature, such as gravity. This was known as superstring theory, and it required the existence of extra dimensions beyond the familiar space and time. Over the following decades string theory underwent a lot of changes. Many new types were introduced (such as the Type I, Type II, Hetrotic Strings, etc). Further- more the introduction of mathematical tools such as mirror symmetry and duality, and the introduction of the M-theory framework that aims to unify and synthesise all the types of string theory[2] have only refined this theory of everything.

History of Dark Matter

The concept of dark matter first came up in the 1930s[3]. An astronomer by the name of Fritz Zwicky made an astonishing discovery about the motion of galaxies in galaxy clusters. He found that visible matter, in these clusters, could not account for the gravitational forces holding them together. To put it simply, there was more mass there than could be accounted for by the visible matter alone. Zwicky referred to this term as ”dark matter.” For a long while after the original discovery dark matter remained a controversial concept in the scientific community. Some argued it is simply a testament to an incomplete understanding of gravity while others argued it may be exotic matter that has not been discovered yet.

This all began to change in the 1970s[4]. As new observations of the rotational motions of galaxies and other stellar objects began to provide more evidence for the existence of dark matter. Astronomers noticed that the galaxies did not follow a pattern that could be based on visible matter alone. This in turn suggested that there was a bunch of ”invisible” matter contributing to the gravitational forces that were holding all galaxies together. Dark matter was further evidenced in the late 1990s and 2000s as new technologies emerged like gravitational lensing and cosmic background microwave radiation[5], and these only further provided evidence for the fact that the universe likely contains a lot more mass than is accounted for by visible mass alone. This served as further evidence and is what led to dark matter becoming as prominent of a field as it is today.

Connecting the histories

Despite the fact that they initially developed as in- dependent academic disciplines, the history of string theory and the history of dark matter are intertwined in a number of ways. The investigation of the strong nuclear force and the behaviour of hadrons by physicists throughout the late 1960s and early 1970s is where string theory first emerged. String theory had its origins in Gabriele Veneziano’s research on the scattering amplitudes of hadrons using the Euler beta function. The behaviour of these particles could be accurately explained mathematically. When astronomer Fritz Zwicky noticed that the apparent mass in galaxy clusters was insufficient to explain the gravitational forces keeping them together, the idea of dark matter began to take shape. He came up with the phrase ”dark matter” to refer to the unobservable substance that is causing these gravitational forces. The study of dual resonance models, which sought to explain the behaviour of hadrons by employing vibrating strings as fundamental objects, was first incorporated into string theory in the 1970s. This established a crucial link between the newly developed discipline of string theory and our understanding of dark matter-influenced particles like hadrons. Scientists started to investigate the role of dark matter within the context of string theory as observational evidence for dark matter grew, such as the rotational motions of galaxies recorded by Vera Rubin and others in the 1970s. Beyond the known components of the Standard Model of particle physics, the additional particles or modes that occur in string theory offered a potential explanation for the nature of dark matter. It’s crucial to remember that string theory still faces difficulties in precisely identifying dark matter particles. The precise characteristics and behaviour of these particles within string theory are currently unknown, despite the fact that string theory provides a theoretical framework that might include new particles that might be candidates for dark matter. In conclusion, the history of dark matter and string theory are intertwined in that string theory offers a framework within which the nature of dark matter may be explained by the existence of extra particles outside of the Standard Model. However, in both areas of research, there are still unanswered concerns regarding the detection and comprehension of dark matter particles within the framework of string theory.

String Theory

The entire point of a theory such as string theory is that it unifies Quantum Mechanics with Relativity. The following section will provide a little background on each one of them.

Development

Theory of relativity The Theory of Relativity is a combination of two inter- twined theories. Special and General Relativity. Special Relativity was developed first in 1905 by Albert Einstein and General Relativity was developed between 1907 and 1915 by Einstein.

Special Relativity is based on the idea that the laws of physics are the same for all observers across the universe regardless of the point of view of the observer given that they are in uniform motion relative to one another[6]. Special Relativity introduced the famous equation:

$$E^2 = p^2c^2 + m^2c^4 \tag{2}$$

This equation relates mass and energy and implicates that a large amount of mass (m) can be transformed into a large amount of energy (e) and vice-versa. An- other one of the key concepts of this theory is that the laws of physics are also same for all inertial frames of reference which means that there is no preferred frame of reference and that the measures of time, distance and other physical quantities all depend upon the observer’s relative motion. Another important concept is the effect of time dilation. The equation for the same is given below:

$$t = r\frac{t_0}{1-\frac{v^2}{c^2}} \tag{3}$$

This is an interesting topic that talks about how time seems to pass by slower for two observers in relative motion with one another. This also means that an object travelling at the speed of light will not experience time at all or time will freeze for the observer moving at c (The speed of light). This effect has been observed and evidenced in various experiments such as the famous Hafele-Keating experiment[7]. This experiment the time dilation of atomic clocks all across the world that were flown in opposite directions. Another interesting phenomenon to note here is length contraction. A key idea in the theory of relativity is the concept of length contraction, which states that when an object is examined from a stationary frame of reference, it appears shorter along the direction of motion. According to Einstein's theory, when an item moves closer to the speed of light, its length relative to an observer standing still appears to be getting shorter. The time dilation effect, which causes time to move more slowly for moving objects, causes this occurrence. The interconnection of space and time in the structure of the cosmos is therefore a result of length contraction, showcasing the fascinating nature of relativistic physics.

Counter-intuitively, General Relativity is what acts as a sort of background for Special Relativity, even though it was discovered later. General Relativity is what is considered a "pillar" of physics along with quantum mechanics. The key concept in this theory is that mass causes a distortion in the space time continuum. Mass bends spacetime and spacetime tells matter where to move. This distortion causes a curvature in the fabric of space time itself and acts as gravity. This effect is often thought of as a result of the tendencies of objects to follow the shortest path possible.[8]. One of the major predictions that this theory made was the existence if gravitational waves which are ripples in the fabric of space time caused by the motion of massive objects. These waves were evidenced in 2015 almost a century after Einstein's original paper. Another important prediction was the fact that light should bend around massive objects because of the curvature in space, this was famously observed during a solar eclipse in 1919[9] where the position of the starts appeared to be shifted.

Finally, one of the most outstanding predictions was the existence of black holes. This theory has been through vigorous testing, from Redshift in mercury to time dilation in atomic clocks that are in orbit.

Quantum Mechanics Quantum mechanics deals with particles at a very small scale, also known as the subatomic scale. It is based upon a set of principles that are a more refined version of classical physics, which governs the movement of macroscopic objects. Wave-particle duality is one of the key ideas in quantum mechanics. This principle states that particles can possess both wave-like and particle-like characteristics. For instance electrons can behave like waves and particles both under different conditions. The wave function(Ψ), a mathematical function that expresses the likelihood of finding a particle in some specified region, provides a mathematical description of this notion.[10] The idea of superposition is another crucial one in quantum physics. Particles have the problability of existing simultaneously in multiple states in accordance with this principle. An electron, for instance, can exist simultaneously in two distinct energy levels. The superposition principle, which asserts that the wave function of a particle may be expressed as a linear combination of its potential states, mathematically expresses this idea. The basic idea is that a combination of solutions to a linear equation is also a solution of it. If this is true, the equation follows the superposition principle. Another crucial idea in quantum mechanics is entanglement[11]. This idea states that particles can become entangled with one another, correlating their attributes as a result. For instance, when two particles are entangled, no matter how far apart they are, measuring the property of one particle might instantly change the property of the other particle. The entanglement principle, which states that the wave function of a system containing numerous particles can be expressed as a superposition of entangled states, mathematically expresses this notion. The Schrodinger equation, a partial differential equation that describes how the wave function of a particle changes over time, serves as the foundation for the mathematical formalism of quantum mechanics:

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left[\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x,t)\right]\psi(x,t) \tag{4}$$

A fundamental framework in theoretical physics known as quantum field theory (QFT) defines how minuscule particles behave and interact. It involves the concept of fields, which are mathematical structures that define the characteristics of particles and their interactions. It is an extension of quantum mechanics. Fields are continuous and deterministic in classical physics. For instance, a mathematical equation can be used to represent the strength and direction of the electric field surrounding a charged particle at any location in space. This is expressed as such:

$$E = \frac{F}{g} \tag{5}$$

Yet, wave functions that are probabilistic and non- deterministic are used to explain particles in quantum physics[12]. Particles are viewed as disturbances or excitations of their respective fields in QFT. These fields are present everywhere in space and time, and the behaviour of particles depends on these fields' characteristics. For in- stance, whereas the Higgs field provides particles mass, the electromagnetic field controls how charged particles interact with one another. A QFT that describes the interactions between particles and their associated fields is the Standard Model of particle physics[13]. Quarks and electrons are examples of fundamental particles in this concept that are excitations of their respective fields. The exchange of other particles, such as photons and W and Z bosons , mediates the interactions between these particles. One of the key ideas of QFT is the idea of particle-wave duality. According to this theory, particles can exhibit both particle- and wave-like behaviour depending on the circumstances. For instance, in a double- slit experiment, electrons can behave like waves, but when they are detected by a detector, they behave like particles. To explain the behaviour of particles, QFT combines wave equations and operators. Operators are mathematical constructs that affect wave functions and characterise particle behaviour. In a quantum system, they are used to determine the probabilities of various outcomes. Another significant concept that QFT introduces is quantization. In this method, a classical field is viewed as an operator that creates and eliminates particles. This permits us to use probabilities rather than predefined outcomes to describe the behaviour of particles[14].

Models of String Theory

The following section talk about different models of string theory and how each one of them works.

SupersymmetrySupersymmetry is a concept in theoretical physics that predicts a symmetry between particles with integer spin (bosons) and those with half-integer spin (fermions). The idea of supersymmetry plays a crucial role in string theory, which is a theoretical frame- work that attempts to describe all fundamental particles and their interactions in terms of tiny, one-dimensional ”strings” that vibrate at different frequencies. The string theory supersymmetry model, commonly referred to as superstring theory or supersymmetric string theory, is an addition to the original string theory that contains supersymmetry. According to this theory, every particle in nature has a ”superpartner” particle that is a half-unit different from it in terms of spin. For instance, the selectron, a superpartner of the electron with spin 1/2, would have spin 0. It’s vital to remember, though, that the superpartner’s spin need not always be a half less than that of the original particle. The particular supersymmetry model under consideration will decide the precise spin values of superpartners. The electron (spin 1/2) in the given case is coupled to a superparticle known as the selectron, which has spin 0. This decision is based on the supplied supersymmetry model’s specific symmetric characteristics and particle content. In general, the superpartner’s spin can change depending on the particular particle and supersymmetry model being taken into account. The fact that supersymmetry in string theory aids in resolving issues with the Standard Model of particle physics, such as the hierarchy issue and the unification of the fundamental forces, is one of its main advantages. The hierarchy problem is the puzzle of why the radioactive decay-causing weak force is so much weaker than the other fundamental forces. New particles that could help explain this mismatch are predicted by supersymmetry.

Depending on the number of dimensions and the precise mathematical structure employed to represent the strings, there are various variations of supersymmetric string theory. The most popular variations include:

- Type I string theory: A type of string theory that incorporates both open and closed strings, allowing for the presence of unoriented strings.

- Type II string theory is a branch of string theory that consists of two distinct but related versions: Type IIA and Type IIB. These theories involve only closed strings, which can vibrate in various modes and interact with each other. Type II string theory also includes supersymmetry, a fundamental symmetry that relates bosons and fermions, allowing for a more comprehensive understanding of particle interactions.

- Heterotic string theory: A type of string theory that combines elements of both open and closed strings, incorporating both left-moving and right- moving excitations.

There are several equations that are used to describe the supersymmetric model. One of them is the World- sheet Action:

$$S = \frac{T}{2}\int d^2\sigma\sqrt{-h}h^{ab}g_{\nu\mu}\partial_a X^{\mu}(\sigma)\partial_b X^{\nu}(\sigma) \tag{6}$$

The motion of strings across spacetime is described by this equation. It includes terms for the string tension, the curvature of spacetime, and the coupling between the strings and other particles. It is also known as the Polyakov action.

The Kaluza-Klien Model Theodor Kaluza and Oskar Klein proposed the Kaluza-Klein (KK) model as a theoretical framework in the 1920s. The model introduced an additional dimension, referred to as the fourth dimension, alongside the three spatial dimensions and one temporal dimension of traditional spacetime, with the goal of bringing together Maxwell’s theory of electromagnetic and Einstein’s the- ory of general relativity. The additional fifth dimension in the KK model is compactified, or ”rolled up” or ”curled,” into a very small size that is far smaller than the other dimensions, rendering it intangible at macroscopic scales. A periodic function, such as a sine or co- sine function, which has a distinctive length scale known as the compactification radius, can explain the geometry of this fifth dimension, which is considered to be a circle. According to the KK model, the apparent electro- magnetic field is essentially a manifestation of the fifth- dimensional spacetime curvature. A four-dimensional vector potential (this exists in a 5 dimensional Klauza- Klien model due to the the mathematical structure and geometry of the compactified spacetime, allowing for the description of electromagnetic phenomena within our observed four-dimensional spacetime.), which comprises the standard three spatial dimensions as well as an additional compactified dimension, specifically describes the electromagnetic field. By the Maxwell equations, this vector potential is connected to the tensor of the electromagnetic field strength. The equation for the same is provided below:

$$F = (E + v * B) \tag{7}$$

The prediction of the development of novel particles known as Kaluza-Klein modes is one of the most important parts of the Kaluza-Klein model. These modes come from the discrete "excitation" levels connected to momentum along the additional dimension that are produced as a result of the quantization of momentum along the compactified fifth dimension. Surprisingly, the quantum numbers of these Kaluza-Klein modes match those of the well-known particles in the standard model of particle physics. However, the momentum in the extra dimension is connected to their additional excitation levels. Larger dimensions and other fundamental forces, such the strong and weak nuclear forces, have been incorporated into Kaluza-Klein model extensions. This model has been used to develop theories of quantum gravity and to address the particle physics hierarchy problem. The Maxwell equations, which regulate the behaviour of electromagnetic fields, and the Einstein field equations, which define the curvature of spacetime in the presence of matter and energy, are essential to the KK model. The fifth dimension is often represented by a cir- cle with radius R in the compactification scheme, adding periodicity to the equations. The intriguing Kaluza- Klein mode prediction results from quantization of momentum in the fifth dimension using units of 1/R.

AxionsAxions are hypothetical particles that Roberto Peccei and Helen Quinn first proposed in 1977 to explain the strong CP problem. A theoretical conundrum in particle physics involving the symmetry of charge conjugation (C) and parity (P) is known as the "strong CP problem." These symmetries are assumed to be retained in the standard model of particle physics, which means that certain processes should be equally likely to take place whether they go through charge conjugation or parity transformations.The strong CP problem, how- ever, arises because it appears that the strong nuclear force's observed behaviour (as defined by quantum chromodynamics, or QCD) violates this presumption. The theta term, which deviates from both the C and P symmetries, is permitted by the mathematical foundation of quantum gravity. The electric dipole moment (EDM) of the neutron, a quantifiable effect that hasn't been seen experimentally, would result from the presence of a non-zero theta component.In order to understand why the theta term in QCD seems to be extremely small or exactly zero, leading to the conservation of CP symmetry in the strong nuclear force, one must first understand the strong CP problem. Many solutions have been suggested, including the Peccei-Quinn mechanism, which dynamically suppresses the theta term and resolves the strong CP problem without contradicting experimental findings. This process creates a new symmetry known as the Peccei-Quinn symmetry. It is difficult to detect the axion field experimentally due to its expected low mass and weak interactions with other particles. The behavior of the axion field in different environments is determined by the axion potential, which is a potential energy function specific to the axion field. The equation for the same is given below:

$$V_m = 60log\frac{[K^+]_0 + a\,[Na^+]_0}{[K^+]_i + a\,[Na^+]_i}(mv) \tag{8}$$

The axion field's specific value, known as the axion misalignment angle, is represented by a flat region at the top of the "Mexican hat"-shaped axion potential. Ax- ions are frequently considered a candidate for dark matter, a mysterious substance that is thought to account for about 85% of the universe's matter. Due to its low mass and lack of interactions, the axion is a good candidate for dark matter because it was not found in previous searches for other types of dark matter. The Klein- Gordon equation holds true for the complex scalar field that mathematically describes the axion field. A sine or cosine function, whose periodicity is related to the strong nuclear force scale, is frequently used to model the axion potential. The Axion Dark Matter experiment (ADMX) and the International Axion Observatory (IAXO) are two of the proposed experiments to look for axions in recent years. Solar axion detection and resonant cavity detection are two of the many methods used in these experiments to look for the weak signals that axions, if they exist, would produce.

In string theory, axions are naturally present as moduli fields, which are scalar fields that describe the shape and size of extra dimensions beyond the usual four dimensions of spacetime. These moduli fields arise from the fact that string theory predicts the existence of extra dimensions, which are compactified to a small size in order to reproduce the observed four-dimensional world. Axions can arise as the imaginary part of the complex scalar fields that describe the size and shape of these extra dimensions. The axion field is associated with a closed string mode that has zero mass and zero spin, and is related to the motion of branes in the compactified dimensions. In string theory, axions can play a role in solving the cosmological constant problem, which is the problem of explaining why the observed value of the cosmological constant is much smaller than the value predicted by particle physics theories. One proposal for solving this problem is the so-called "axiverse" scenario, which postulates the existence of a large number of ax- ions with a wide range of masses, all of which couple very weakly to other particles. The axiverse scenario arises from the fact that the compactification of extra dimensions in string theory leads to a large number of moduli fields, including the axion field, that can take on different values in different regions of spacetime. The different values of the axion field lead to different values of the effective cosmological constant, which can cancel out to give a small observed value. Axions can also play a role in inflationary cosmology, which is the theory that describes the rapid expansion of the universe in the first fraction of a second after the Big Bang. In some models of inflation, axion fields can provide the inflaton field that drives the inflationary expansion. These models are called axion inflation models, and they predict specific features in the cosmic microwave background radiation that can be tested by observational data.

Dark Matter

Development

The first evidence for dark matter came from examinations of galaxy rotation curves, which show that the outer regions of galaxies rotate more quickly than would be predicted based on the visible matter present. Since then, however, several independent sources of dark matter, including the distribution of galaxies and the cosmic microwave background radiation, have been discovered.

The high temperature of the early cosmos led to the ionisation of atoms, which created an opaque environment where light was absorbed and reemitted. As cooling atoms finally formed, all light fled and spread over the cosmos. When the universe expanded, the wavelength of this light changed from gamma rays to microwave radiation, which can now be seen. This radiation's brightness makes it possible to gauge the distribution of dark matter, adding to the body of data supporting its existence. Neutrinos, which were once thought to be a viable con- tender but are now known to be excessively hot, were excluded by further limits on the nature of dark matter. According to current beliefs, dark matter is cold, consisting of massive, inert particles that cluster together into halos close to their original locations. Current research continues to shed light on this enigmatic element, with researchers employing particle accelerators and monitoring signals in space to narrow down what dark matter could be.

Models of Dark Matter

SIMPDespite their name, Strongly Interacting Massive Particles (SIMPs), a putative class of dark matter particles, only interact weakly with visible matter. Comparatively more difficult to detect than other dark matter candidates, SIMPs are predicted to have weak interactions with both visible matter and other SIMPs. It is challenging for SIMPs to directly interact with or be discovered by conventional experimental techniques because of their weak interactions. However, to perhaps find the elusive presence of SIMPs and better comprehend their function in the cosmos, scientists continue to investigate novel approaches, such as sensitive detectors and improved methodologies.

WIMPWeakly Interacting Massive Particles, or WIMPs, are a hypothetical class of particles that are frequently thought of as potential dark matter candidates. WIMPs are thought to interact poorly with visible matter and with other WIMPS, which makes them more elusive to discover than SIMPs. WIMPs are proposed as a kind of particles that interact mostly through the weak nu- clear force, one of the four fundamental forces of nature. Because of this, WIMPs are frequently proposed as a potential explanation for dark matter. This implies that WIMPs would interact with other particles, including visible matter, very weakly. Weakly Interacting Mas- sive Particles, or WIMPs, are a subclass of The formation of halos surrounding galaxies, which would act as the gravitational ”glue” needed to prevent galaxies from breaking apart, is one of the predictions of WIMP models. The WIMPs in these halos would be undetected and unseen since they would not significantly interact with visible matter. Several experimental projects are looking for WIMPs right now, employing a range of tools like particle accelerators, telescopes, and subterranean detectors. If WIMPs are found, it will help us better comprehend the nature of the cosmos at its most fundamental level and will give important evidence for the presence of dark matter.

Light Dark MatterA class of dark matter particles with masses typically with less than a few GeV (gigaelectronvolts) are referred described as ”light dark matter”. The terms ”fuzzy dark matter” and ”ultralight dark matter” are frequently used to describe these particles. One of the main hypotheses for light dark matter is that it might be composed of particles comparable to the Higgs boson, a particle that is known to exist and is essential to the process by which particles acquire mass. ALPs, or axion-like particles, are speculative particles that may have masses ranging from a few microelectronvolts to a few millielectronvolts. Since light dark matter particles would only have very weak interactions with visible matter, their detection is challenging. Looking for their effects on cosmic formations like galaxies and galaxy clusters is one possible method of finding them. Observing the effects of light dark matter on the cosmic microwave background radiation, a byproduct of the early universe and a valuable source of information about dark matter, is another option. Experiments using specialised detectors to check for incredibly weak signals that might be created by interactions between light dark matter particles and visible matter are only one of the several cur- rent experimental efforts to search for light dark matter. Identifying light dark matter would be a significant advance in our understanding of the universe and the fundamental forces that govern it.

Synthesis

SIMP and SUZY

The supersymmetric string theory, or SUZY model, fuses general relativity and quantum physics. The hierarchy problem and the existence of dark matter are suggested to be solved by the existence of supersymmetric particles as companions to known elementary particles. The SIMP model, in contrast, proposes dark matter particles with masses ranging from a few GeV to a few hundred GeV, a new strong force, and strong interactions with each other but weak interactions with ordinary matter. SIMPs may be able to explain some of the small-scale structural observations that WIMPs struggle with, in contrast to WIMPs, another type of fictitious dark matter particles that interact weakly with both dark matter and normal matter. There are some potential linkages between the SUZY and SIMP models notwithstanding their differences. The lightest super- symmetric particle (LSP) is a potential candidate for dark matter in the SUZY model, and in some cases, the LSP might even be a SIMP. As a result, the SIMP model might be a way to put the SUZY model to the test and possibly offer proof that supersymmetric particles exist. The Higgs boson is another possible link between the SUZY and SIMP models. The Higgs boson has a supersymmetric partner called the Higgsino in the SUZY model. The SIMP model might also be a technique to test the SUZY model through the Higgsino since in some cases, the Higgsino can be both an LSP and a SIMP. The SUZY and SIMP models are fundamentally separate theoretical frameworks, yet they may be connected in various ways, particularly when looking for dark matter particles. To put these theories to the test and perhaps find novel physics outside of the Standard Model, more investigation and experiments are required.

Kaluza - Klien and WIMP

WIMPs are hypothetical dark matter particles that interact with matter in a weak way through the weak nu- clear force and gravity. Their existence has not been established despite numerous searches. The Kaluza-Klein hypothesis, in contrast, adds additional dimensions to spacetime that are compactified and are not visible at greater scales. These extra dimensions have been incor- porated into particle physics models created using this framework. A key notion in string theory is the idea of string compactification. It entails compactifying the extra dimensions in such a way that particles that can be seen at low energies can form. In this technique, the extra dimensions are chosen in a specific arrange- ment that affects the properties of the resultant parti- cles. The so-called Calabi-Yau manifolds, which have intricate geometries, are used to explain the potential configurations of the additional dimensions. WIMPs and Kaluza-Klein theory are related because in some KK theory models, the extra dimensions can produce par- ticles with characteristics resembling those of WIMPs. They are known as Kaluza-Klein particles and can have a variety of masses and interaction energies. Similar to the lightest supersymmetric particle in the SUZY model, the lightest Kaluza-Klein particle may occasionally be a candidate for dark matter. The size of the parameter space for Kaluza-Klein and WIMPs varies depending on the model under consideration. WIMPs typically range in mass from a few GeV to many TeV, and their in- teractions with regular matter are weak. Depending on the particular model being studied, Kaluza-Klein parti- cles can have masses ranging from a few hundred GeV to several TeV, and the strength of their interactions with conventional matter can be either mild or power- ful. The phenomenology of Kaluza-Klein and WIMPs also depends on the paradigm under consideration. It is difficult to identify WIMPs since they are predicted to seldom interact with normal matter. However, they might be able to be found indirectly, perhaps by look- ing for their annihilation byproducts in cosmic rays. On the other side, Kaluza-Klein particles might be created in high-energy particle collisions, and their decay prod- ucts might be found in tests. In conclusion, even though Kaluza-Klein particles and WIMPs are two quite sepa- rate theoretical ideas, there are some overlaps in their prospective applications as dark matter possibilities. To put these theories to the test and perhaps find novel physics outside of the Standard Model, more investigation and experiments are required.

Axions and Light Dark Matter

The strong CP problem in particle physics, which has to do with the conservation of CP symmetry in the strong nuclear force, has been solved by the hypothetical particles known as axeions. Axions are revealed as a solution by addressing the issue that the symmetry's existence implies. Another category of dark matter pos- sibilities, known as light dark matter (LDM), has masses between meV and gev, making it lighter than ordinary WIMPs. Dark photons and dark scalars, which are predicted by a number of theories beyond the Standard Model and have weak interactions with ordinary matter, are examples of particles included in the LDM. Axions and LDM are related because in some string theory models, the axion field can be connected to the hidden sector of the theory, which is responsible for dark matter's existence. Axion-like particles (ALPs), which resemble axions but have differing masses and interaction strengths, can be created as a result of this coupling. The size of the parameter space for axions and LDM varies depend- ing on the particular model under consideration. Ax- ions normally have a mass range between a few micro- and several milli-electronvolts, whereas LDM typically has a mass range between MeV and GeV. These particles can have weak interactions with ordinary matter, which makes it difficult to detect them. The particular model under consideration will also affect the phenomenology of axions and LDM. Axions are generally thought to interact with ordinary matter infrequently, making it difficult to detect them. Their conversion to photons in strong magnetic fields or their impact on the cosmic microwave background radiation are two potential detection methods. The direct detection of LDM, on the other hand, might be accomplished by the use of cryogenic detectors or bubble chambers. In conclusion, although axions and LDM are distinct theoretical ideas, there are some linkages between them due to their potential to serve as dark matter candidates. To put these theories to the test and perhaps find novel physics outside of the Standard Model, more investigation and experiments are required.

Conclusion

Here is a list that summarizes all the points discussed in the Synthesis section:

Supersymmetric String Theory (SUZY Model): Supersymmetric particles are proposed as companions to known elementary particles to solve the hierarchy problem and explain dark matter. The lightest supersymmetric particle (LSP) in the SUZY model is a potential candidate for dark matter.

In some cases, the LSP might also be a Strongly Interacting Massive Particle (SIMP), which is another type of dark matter particle with strong interactions among themselves but weak interactions with ordinary matter. The existence of SIMPs in the SUZY model can help explain small-scale structural observations that WIMPs struggle with.

The Higgs boson and its supersymmetric partner, the Higgsino, provide a possible link between the SUZY and SIMP models.

Kaluza-Klein Theory: Kaluza-Klein theory incorporates additional compactified dimensions in spacetime, which are not visible at larger scales. In some Kaluza-Klein models, the extra dimensions can give rise to Kaluza-Klein particles with characteristics resembling those of Weakly Interacting Massive Particles (WIMPs).

The lightest Kaluza-Klein particle may occasionally be a candidate for dark matter.

The parameter space for Kaluza-Klein particles and WIMPs varies depending on the specific model under consideration.

Axion and Light Dark Matter (LDM): Axions are hypothetical particles that solve the strong CP problem in particle physics and are related to the conservation of CP symmetry in the strong nuclear force.

Axions can be connected to the hidden sector of string theory, which is responsible for the existence of dark matter.

Axion like particles (ALPs) can be created in string theory models and have different masses and interaction strengths compared to axions.

Light Dark Matter (LDM) refers to dark matter candidates with masses between meV and GeV, making them lighter than ordinary WIMPs.

Dark photons and dark scalars, predicted by theories beyond the Standard Model, are examples of particles included in LDM.

The detection of axions and LDM is challenging due to their weak interactions with ordinary matter, but various detection methods are being explored.

The investigation of dark matter and string theory is still an active field of study with promising potential. The direct discovery of dark matter particles, including as WIMPs, axions, and light dark matter, is currently the subject of numerous experimental investigations utilising a wide range of detection techniques. These initiatives include astrophysical studies, under- ground experiments, and particle colliders. In the mean- time, the advancement of string theory continues to offer fresh perspectives on the underlying makeup of particles and the cosmos. Many intriguing models have been developed as a result of the concept of string compactification, which enables the construction of particle models with certain features and may be evaluated in upcoming studies. Overall, these fields appear to have a bright future ahead of them, with many fascinating discoveries possibly on the horizon. We can anticipate learning more about the nature of dark matter and the underlying structure of the cosmos as experimental methods advance and theoretical models are improved.

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