The Holes in our Universe: Beyond the Standard Model

Garrett Chong

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This paper explores the Standard Model of particle physics, its shortcomings, and topics that go beyond the Standard Model. The Standard Model is a theory that explains the fundamental particles and forces that govern our universe on the quantum scale. The Standard Model has been a phenomenologically accurate theory that has predicted many aspects of our world with impressive consistency, but falls short in many places. Some main topics that are not explained by the Standard Model are baryon asymmetry, dark matter, and gravity. Scientists have proposed a plethora of theories that try to amend these problems, known as Beyond Standard Model (BSM) physics. Many of these topics can be intriguing, but the complexity can often be overwhelming and deter new investigators. This paper serves to elucidate the technical aspects of BSM physics and make these topics more accessible to those with a highschool level physics background.

Keywords: Standard Model, Beyond Standard Model, Quantum, Particle, Baryon asymmetry, Dark matter, Gravity, Theory

Introduction

The field of high energy physics deals with how the universe works at its largest and smallest extremes. Understanding how the most fundamental building blocks of the universe work is imperative to understanding its mysteries on larger scales. Eventually, if physicists are able to unite the immense and the miniscule into one model, they will finally have a Theory of Everything that explains our universe. Thus, this field is of great interest to modern scientists. Physicists currently have two major models that dominate physics: relativity and the Standard Model. In this paper I will focus on the Standard Model, but also talk about its incompatibilities in relation to relativity.

Many of us may be familiar with General Relativity and Special Relativity already. These were developed by Albert Einstein in the early 1900s and explained important aspects of spacetime. General Relativity describes gravity as a field that results from mass bending spacetime. But because space and time are combined into the singular "spacetime" in relativity, regions of high gravitational potential must affect time as well. Special Relativity describes the way velocity impacts space, time, and mass. The core idea of Special Relativity is that all motion in the universe is relative and changes based upon one's reference frame–which is determined by position and velocity–and that speed of light is always constant no matter what reference frame you are in. For example, suppose there is an observer watching a train go by at 100 mph. The observer is seeing it move at 100 mph, but from the perspective of a person inside the train, the observer is moving in the opposite direction at 100 mph. So if both inertial reference frames are valid to the universe, then who is really moving? In addition to that, if both people measured the speed of light in their different reference frames, they would both measure the same speed. Therefore, time and the way one perceives the universe changes based on one's reference frame; in other words, time is relative.

The Standard Model, on the other hand, in some ways disagrees with the other two. It describes the fundamental particles and forces that build the universe as well as how they interact to form bigger and more complex things. The Standard Model has been hugely successful in predicting many interactions and particles that scientists have found today, but has a few core problems that prevents it from linking with General Relativity and Special Relativity to create the Theory of Everything. So, what are the issues with the Standard Model? To answer this question, we must first understand the Standard Model itself. The goal of this paper is to explore the shortcomings of the Standard Model. The remainder of this text will be spent investigating the Standard Model and problems that it cannot explain, including gravity, baryon asymmetry, and dark matter.

Introduction to the Standard Model

The Standard Model has been our best theory for understanding all of the smallest possible particles and forces that make up our universe. Despite being on a smaller scale than giant stars and galaxies, it is not less complex. The Standard Model describes different particles and the forces and interactions that occur between them, which is generally represented with a table that makes visualization easier. This table is split into two main groups, the fermions and the bosons, with each having two smaller subsections.

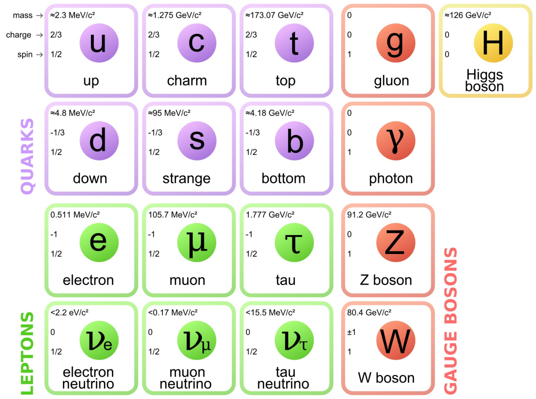

Fig. 1 Image of Standard Model diagram[1].

The fermion group comprises the baryons and leptons, which make up all the matter we can see in our universe. The baryon group is made of six particles known as quarks. These particles bind together to form larger particles like protons and neutrons[2]. There are three generations of quarks, with each generation being identical but heavier than the previous[3]. The most basic and common of these are the up quarks with a $+\frac{2}{3}$ charge, and the down quarks with a $-\frac{2}{3}$ charge, which make up the first generation[3]. The second generation consists of the charm and strange quark, and then the third generation has top and bottom.

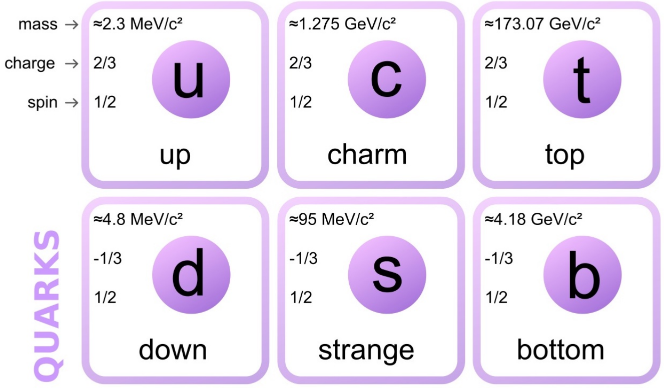

Fig. 2 Image of baryon group in Standard Model diagram[1].

Quarks also have a property known as color, described as either red, green, or blue. Their color determines how they interact with the strong force. These are not the actual colors of the particles, but rather a way of visualizing different types of quarks. It is important to note that free particles composed of quarks must have no net color charge[3]. Then finally, quarks have a property called spin. A particle can either have a left-handed spin, meaning they spin in the opposite direction as their motion, or a right-handed spin, meaning they spin in the same direction as their motion[3]. Spin is something that applies to every particle of the Standard Model, and is not unique to fermions. Left-handed up and down quarks can turn into each other via the exchange of a W boson, but right-handed quarks cannot do so since a right-handed W boson does not exist[3]. A small amount of weak interaction occurs between left-handed quarks of different generations, meaning that it is possible for an up quark to spit out a W+ boson and become a strange quark, so transition between generations is possible[3].

Leptons, similarly to the baryons, also have the structure of two types of particles with three generations[3]. The first type is the electron, which is a -1 charged particle with a very small mass. The second type is the neutrino, which is similar to the electron, but has no electric charge. Their increasing generations become the muon/muon neutrino, and then the tau/tau neutrino[3]. Similarly to quarks, left-handed leptons can transform between being charged or being a neutrino via the weak force, but unlike quarks, leptons do not have color charge and therefore cannot interact via the strong force[3].

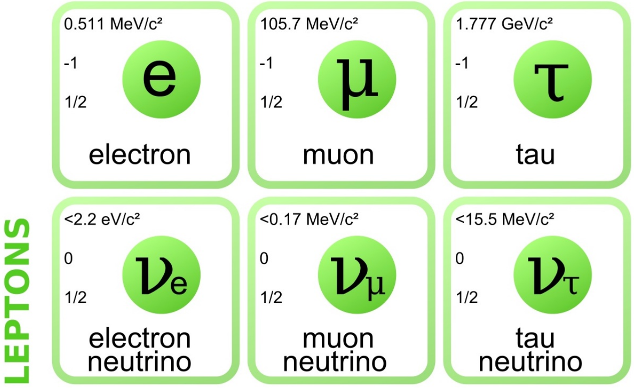

Fig. 3 Image of lepton group in Standard Model diagram[1].

The Standard Model also has a group called the bosons, though this group has far fewer members than the fermions. Bosons are known as the force carrier particles because most of them are responsible for carrying out the interactions due to the fundamental forces[2]. There are two subsections of this group, the gauge bosons and the Higgs boson. Of the gauge bosons, there is the W boson, the Z boson, the gluon, and the photon. The W boson is the carrier of the weak force and can come with a 1+ or 1- charge as well as left-handed spin. It is responsible for the radioactive decay of atoms, meaning it is involved with nuclear fission and fusion. The Z boson also carries the weak force and is very similar to the W boson, but does not have a charge and has a spin of 0 or 1[2,3]. The gluon is the carrier of the strong force and is responsible for binding quarks together to form larger particles. Gluons also have color charges like quarks but do not have any mass, which makes them vector gauge bosons[2,3]. Lastly, the photon is the carrier of the electromagnetic force. The photon is also a massless gauge boson and is responsible for all light in the universe. However, notably, these gauge bosons only account for three of the four fundamental forces, with gravity being absent[3].

The second group of bosons only has one member, the Higgs boson. This particle is an excitation of something called the Higgs field, which is responsible for giving all matter in the universe its mass[3]. The way this happens is that when a left-handed particle is moving and collides with a Higgs boson, it will be deflected and reverse its spin, becoming right-handed. This particle will travel until colliding with another Higgs boson which deflects and reverses its spin again[3]. This interaction with the Higgs field slows the particle down and gives it mass, and the more a particle interacts with Higgs bosons, the higher the mass it will have[3].

Beyond the Standard Model

Despite seeming extremely thorough and complex, the Standard Model has a few critical issues that science is currently working to resolve. Some of these main issues are the Standard Model's inability to explain gravity, baryon asymmetry, and dark matter[2,3]. Gravity is a fundamental force that is entirely left out of the Standard Model. Einstein's relativity has described gravity in a way that works with many of the thing's physicists see in our universe, but this only works on larger scales. On the particle level, physicists do not have a way to fit gravity into our model, and because gravity is a very weak force, it is very hard to test accurately[4]. This has led us to the point where scientists are not exactly sure how to theoretically deal with it, and even if they did, it would be extremely hard to confirm.

Baryon asymmetry is one of the most important phenomena that produces a universe where things can exist, but scientists have no proven explanation for it[5,6]. Baryon asymmetry is the existence of more matter than antimatter (i.e., their asymmetry). Antimatter is just like normal matter, but with opposite charges, such as an electron and a positron[3]. Without this asymmetry, nothing could exist. The Standard Model predicts a universe with equal parts matter and antimatter, but since matter and antimatter immediately annihilate when they come in contact, a universe of equal parts would cancel itself out and stop existing[5]. However, physicists know this is not true because matter does exist, so there must be an asymmetry of matter[5].

Dark matter is something scientists know must exist observationally, but they have yet to learn much about it fundamentally. Dark matter is similar to regular matter since it has a positive mass, and therefore interacts with objects gravitationally. It does not, however, physically interact with any normal matter or itself. This means that it is invisible and cannot touch anything, which makes it extremely difficult to detect and measure in any meaningful way. Astronomers are able to observe the gravitational effects it has on things like light and other bodies, deducing that its particles are likely very massive, but cannot learn anything about the substance itself[6]. Because of this, physicists have no candidate for the Standard Model that is able to explain dark matter. The current name for the hypothetical particle that many scientists believe constitutes dark matter is the weakly interacting massive particle (WIMP)[6]. In summary, we have no way of explaining the behavior of gravity, the effect of baryogenesis, or what dark matter is in our Standard Model.

Gravity

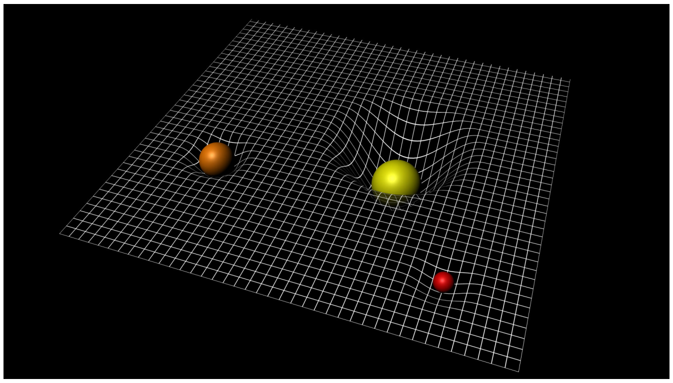

Fig. 4 Visualization of gravity resulting from curved spacetime[7]. The greater the mass of the object, the greater the distortion in spacetime. The gridlines, despite showing as two-dimensional space, are actually representative of four-dimensional spacetime. Image taken from reference[7].

From the perspective of some branches of physics, gravity is one of the four fundamental forces that govern our universe (the others are electromagnetism, the weak force, and the strong force). Unlike the other three, physicists have not found any evidence of a quantized version (or particle) of this force yet. Gravity is currently understood as a result of the geometry of spacetime, similar to how two balls curve while on a tensioned fabric. A major aspect of the Standard Model is that it describes everything like a particle, so our inability to find a force carrier particle for gravity means that it cannot fit into the Standard Model. To visualize how our understanding of gravity behaves, one can imagine oneself walking down a path in a straight line. Then imagine a large massive object to their right on the path, bending space so that their path now curves and leads down into the massive object. No "force" is actually being exerted on them to pull them into the object, but rather their motion is bent with respect to spacetime. This understanding has been extremely accurate in explaining results from experiments and observations that have been made in astronomy, like the motion of planets. But on the smaller scale, this does not hold up quite as well.

Since gravity does not behave the same on the quantum level as it does with planets and galaxies, it is very hard for scientists to link it with the Standard Model. They have theorized a gauge boson particle called the graviton that would include gravity in the model, but it is not as simple as just adding it in. The way the Standard Model works is that it is actually a long equation known as the Standard Model Langrangian[4]. This equation contains terms that account for all the interactions that can occur in our universe. Thus, if physicists try to add the graviton in, other parts would have to change in order to accommodate this new force and keep the balance of the equation[4]. This would either mean that all of the experiments confirming these values were wrong, or the graviton does not fit in the way scientists initially thought. Also, the existence of the graviton is incompatible with General Relativity's explanation of gravity, which is another extremely successful theory for which there is a lot of evidence. The Standard Model describes gauge bosons as particles that carry a quantized amount of some force[4]. This would mean that gravity would be a physical particle that exists in our universe rather than being an effect that results from the bending of spacetime.

Another major issue with the graviton is that it cannot interact over a zero distance[6]. In quantum mechanics, particles can interact over what is called a zero distance. Zero distance is when there is no space between the two interacting particles, so they are both existing at the same point. This causes an issue with the graviton, because when physicists calculate what happens when two gravitons interact over a zero distance, the result is an infinite amount of energy packed into a tiny space which is not possible[8,9]. Then even if the graviton did exist, it would be extremely difficult to detect and measure in experiments because it is by far the weakest of the fundamental forces. Thus, any plausible theories that explain gravity are nearly impossible to accurately test.

One prominent theory that tries to solve quantum gravity and join the Standard Model to Special Relativity is String Theory[8,9]. This is an extremely complex theory that was first postulated during the 1970s, and has since gained and lost traction over time[8]. String Theory has been infamous for being very difficult to understand and very odd. The main idea of this theory is that instead of thinking of particles as singular points, it describes them as one-dimensional lines, or strings. Each particle that exists is simply a vibration in this string, and different vibrational patterns correspond to different kinds of particles. One important thing that this theory does is that it spreads out these graviton-graviton interactions over a larger space, thus solving the issue of the zero distance interaction[7]. While this would seem like a pretty strong explanation, String Theory still has gaps in other areas. It has been losing popularity over the years due to its inability to explain certain other particle behaviors, having many different versions, requiring strange mathematics (like needing ten dimensions to work), and being very hard to test. In summary, the way the Standard Model describes gravity is different from how General Relativity describes gravity, and we do not yet understand how to make both of them work in the same context.

Baryon Asymmetry

Baryon asymmetry is a phenomenon that physicists believe results from intricate interactions on the particle level, but is responsible for things like planets and galaxies being able to exist. Scientists know that there is an asymmetry because of some basic observations that they have made in astronomy. For example, cosmic rays (high energy particles from space) that they receive come from all over the galaxy, and protons outnumber antiprotons ten thousand to one[5]. Also, probes that they have sent to space have never collided with any antimatter and annihilated, which should not be expected if the universe were equal parts matter and antimatter[5]. Scientists would also see far more gamma ray emissions (which result from these annihilation interactions) throughout our galaxy if these annihilations really were occurring, so their absence points towards a matter dominated galaxy[5]. And, if matter and antimatter existed in equal parts, they would be constantly annihilating each other, therefore preventing anything from existing at all.

A physicist named Sakharov found that three conditions must be met for baryon asymmetry to take place. First, there must be a baryon number violation during some phase of the universe[5,6]. What this means is that because of some set of conditions during a period in the universe, the total mass in a reaction was not conserved. So, if three particles reacted, two or four might come out instead, which would lead to an imbalance of matter. The second condition is that there must be a C and CP symmetry violation[5,6]. This refers to the CPT symmetry theory, which stands for charge, parity, and time[5]. This theory says that in every single particle interaction scenario, by flipping the charge (change to antiparticle counterpart), mirroring the positions, and if time were reversed, the laws of physics will remain the same. But individually, any one symmetry can be broken as long as all three are not broken simultaneously[5]. So, this second condition means that during these baryon number violating interactions, there was a break in charge and charge-parity symmetry, resulting in a preference towards matter over antimatter. This is important because even if baryon number violations occurred, the violations could occur for both matter and antimatter, so they would yet again cancel each other out with enough time. The third condition is that there must have been thermodynamic non equilibrium[5,6]. This means that baryon producing reactions must have occurred more slowly than the expansion of the universe during that time. Because of the fast expansion, the rate at which these matter and antimatter pairs annihilate is decreased, which allows for even more baryons to exist[6].

These conditions can actually be met realistically in our current understanding of physics. The grand unified (GUT) scale was a period when the electromagnetic, strong, and weak forces were combined into one particle, known as the electronuclear force[5]. This period would have allowed for the breaking of baryon number symmetry for a period of time. Another possible time period is the electroweak phase transition (EWPT)[5]. This is when the universe had cooled enough for the strong force to separate from the electroweak force, meaning that the electromagnetic and weak forces were still combined while the strong force was its own separate thing. This time period would have allowed for the thermodynamic nonequilibrium required for baryogenesis. Finally, C and CP violations do naturally occur and have been observed experimentally, but have not been seen at large enough scales to explain this large asymmetry that is seen today[5]. Research is still ongoing to figure out in which time period and how this asymmetry occurred, but this still remains a much disputed and unsolved question in physics. In summary, the Standard Model claims that matter should not be able to exist how it does today, and we do not have a fully developed proved theory that explains why the Standard Model is wrong.

Dark Matter

Dark matter is the type of matter that makes up most of our universe, but physicists know close to nothing about it. They know it exists because of the effects it has on its surroundings. Mainly, they can see it as the gravitational force discrepancy in certain phenomena or in the lensing effect it can have on light. Scientists first discovered its existence because when scientists viewed a cluster of stars in space, they were moving very fast and should have escaped the gravitational pull of the cluster. They were able to calculate the force that would be required to hold the cluster together and the amount of force that all the mass in the cluster would generate, and they found that there was not nearly enough visible mass there to produce a gravitational force strong enough to hold it together. This led them to the conclusion that there must be a form of matter that they cannot see, hence the name “dark matter”. They can also see the lensing effects that a large body of dark matter can have on light.

As a large body of dark matter moves in front of something like a star cluster, the light will bend due to the strong gravitational field. The dark matter acts similarly to a gigantic lens, so by studying the bending of the light, physicists can indirectly study this invisible lens in space. Despite being so massive and making up a considerable portion of all matter, the Standard Model does not account for it at all. Thus, scientists began searching for a particle candidate for dark matter.

Since dark matter has a high mass but cannot interact with other matter, the proposed name for it is the WIMP. There have been many possible particles from many different theories that serve as candidates for the WIMP. One candidate is the electrically neutral neutralino particles from next-to-minimal supersymmetry (NMSSM). The neutralino is the super partner to the neutrino in the NMSSM and is a very massive and stable particle, but does not really interact with mass[11]. Another possible candidate is the axion, which was not even originally supposed to explain dark matter. The axion was originally theorized because when physicists looked at the charge distribution of a neutron, it was nearly perfectly distributed even though the particles that made neutrons had charge and should not be symmetric[6]. The axion was proposed as its own field with bosons that suppressed the charge of a neutron. Later, physicists realized that if this axion were real, it would actually be a very effective dark matter candidate due to it being very abundant and not interacting with matter[6]. The axion has been particularly popular recently due to a few possible signals that it may be real, but no conclusive data has actually been found yet to confirm its existence. In summary, dark matter is not included in the Standard Model and it is not clear how it would interact with other standard matter if it was.

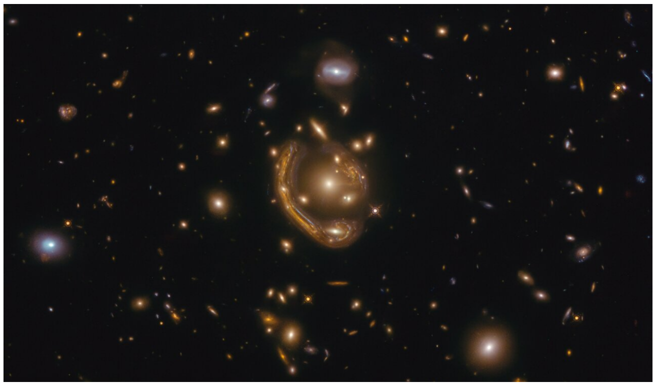

Fig. 5 Image of gravitational lensing of a background galaxy around a foreground elliptical galaxy[10].

There are many ongoing experiments searching for the existence of dark matter. The Large Hadron Collider (LHC) is a prime location where many scientists look for preliminary signals due to the high-energy collisions it produces and its ability to probe many quantum interactions with extreme accuracy. There are also more specialized experiments that search for signals of the different theorized particles. The XENONnT and Large Underground Xenon ZonEd Proportional scintillation in LIquid Noble gasses (LUX ZEPLIN) experiments search for the WIMP by monitoring for theorized interactions with tanks of liquid xenon deep underground[12,13]. They are able to detect nuclear recoils that result from particle interactions, and then single-out for reactions that can only be caused by WIMPS. The University of Chicago’s Broadband Reflector Experiment for Axion Detection (GigaBREAD) experiment utilizes a large cylindrical horn antenna to act as a receiver for dark photons, which would be tested and analyzed after data collection[14]. At

Fermilab, the Axion Dark Matter eXperiment (ADMX) experiment searches for the axion by using an axion haloscope, which behaves much like a radio[15]. It has a low-noise chamber where axion-photon interactions would take place, and the detector can be tuned to certain frequencies that would allow for us to detect and measure these interactions. The ADMX and LUX ZEPLIN experiments seem to be the most promising among the many that are ongoing because they can probe the largest range of masses and energies. In the search for dark matter, experiments are designed to search a certain range of masses or energies at which it could exist. These two experiments have the greatest sensitivity and are able to probe an extremely large range of values for the dark matter particle. The ADMX is sensitive from 2-40 μev and the LUX ZEPLIN is sensitive to 2.3×10^{-43} cm^2 for a 40 GeV/c^2 mass WIMP. Even if they do not find any signals of the WIMP or axion, they will have narrowed down the search significantly for future experiments.

Conclusion

In conclusion, I focused on three major issues of the Standard Model: its inability to explain gravity, baryon asymmetry, and dark matter. It fails to explain gravity because it has no mathematical way to explain it within its defining equations and it would allow for interaction over zero-distance for gravitons, which is not possible. The proposed theory to solve this was String Theory, which describes particles as vibrations or frequencies. Baryon Asymmetry is not explained by the Standard Model because it claims that we should have an equal amount of matter and antimatter, and thus nothing could exist in the universe. Physicists have identified three conditions that allow for baryon asymmetry to happen, called the Sakharov conditions. In our current understanding of physics, we believe that there were certain periods of time during the universe's evolution that would allow for these to take place, but none of them take place at the same time. Finally, the Standard Model cannot explain dark matter because we really do not know much about it, and do not know how to fit it in or the implications it would have on the rest of the model. We know that it exists due to the observations we have on how it interacts with light, but nothing else. Scientists have theorized a few particles that could be dark matter candidates, such as the WIMP, the neutralino, and the axion. There have been a few possible signals that the axion exists, but nothing conclusive. There are many experiments searching for the axion within its possible domain of existence.

Some of the best minds in the history of humanity have worked to create our current models to explain the universe, but as research progresses and our collective knowledge develops, holes will inevitably form in any theory. The deeper scientists dig into these mysteries, the more they realize just how vast they are. Physicists never would have questioned why matter even exists if they did not first discover antimatter; gravity would not be an issue if they never discovered quantum theory; dark matter would never have been discovered without first understanding gravity. Physics beyond the Standard Model works to solve these new mysteries that arise from discovery. Scientists may not know right now, but as research continues, they will. These new findings will spawn more questions that will serve as launchpads for the next generation, allowing them to push the frontier of science even further beyond the Standard Model.

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