AN ANALYSIS OF THEORETICAL AND EXPERIMENT RESULTS TO SET PARAMETERS ON DARK MATTER

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ABSTRACT

Topic: An analysis of theoretical and experiment results to set parameters on dark matter.

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The universe consists of expanding space containing a distribution of matter and energy. In this paper, we discuss dark matter, which is the unseen material in space. This dark matter report examines the reasons why scientists postulate the existence of dark matter. The paper also discusses the properties of dark matter. This paper also discusses the possible candidates of dark matter in the universe. This reports also includes an analysis performed using the findings of the current dark matter detectors to determine the most likely candidates for dark matter. In this section, the paper focuses on determining whether the current detection results rule out any of the suggested dark matter candidates. Finally, the paper outlines the new detector capabilities that are expected to be incorporated into the next generation studies if the current dark matter detectors appear unsuccessful in their ability to detect dark matter particles.

Introduction

Dark matter is the term that describes the unseen mass or material in the sky. Human eyes can see the bright matter in the sky such as stars, but scientists know that some other matter is there since it pulls on the bright matter. The name dark matter, was given since it does not interact with regular light in any form. Dark matter does not collide with ordinary matter, or absorb energy from it and neither can it be seen or detected with any type of equipment created so far by man. Also, the dark matter is the fundamental element of the cosmological structures at the dwarf galaxy scale and above. The proportion of dark matter abundance in the universe is estimated to be over 80 percent. Astronomers estimate that dark matter outweighs normal matter by a factor of 6 to 1. The importance of deriving the basic data on the nature of dark matter, including the mass of its particles, distribution in galaxies, mean temperature and capacity for dissipational collapse, relates to uncovering the properties of dominant species of matter in the universe and extending the standard model of particle physics. These descriptions of dark matter raise the question of whether it even exists.

Reasons that scientists postulate the existence of dark matter

One of the proponents of this belief states that if the universe were assumed to be a pie of matter and energy, and sliced into categories, it would be made up of different proportions. The largest percentage of the entire universe slice, approximately 68 percent, would be made up of dark energy, 27 percent would be composed of dark matter while a mere 5 percent would be composed of regular ordinary matter (Cain, n.d). This 27 percent mysterious matter surrounds galaxies and only interacts with ordinary matter through gravity. The normal 5 percent of the universe is made up of planets, stars, gas, dust, and people. In the recent past, astronomers have developed a better approach to detecting dark matter, through the effect of its gravity on the path that light follows as it crosses the universe. As light travels through dark matter, its path in that region gets distorted by gravity. Hence, rather than following a straight line, the light is bent back and forth depending on how much dark matter it is passing through. Astronomers have even enhanced this technique so that they can map out the regions of dark matter in the sky through looking at the distortions in the light and then working backward to determine how much intervening dark matter would need to be there to cause it. Siegel also demonstrated the existence of dark matter in the universe using five types of evidence. One of the reasons is galaxy clusters. In this reason, Siegel explained that astrophysical objects swirl and orbit: planets revolve our sun, stars orbit around our galactic center, as well as individual galaxies in groups orbit around themselves. The gravitational pull felt by these objects is necessary to balance the energy they have due to their motion; hence keeping the objects tightly bound together. A fast-moving object with more kinetic energy cannot easily keep gravitationally bound unless there is sufficient mass (implying dark matter) to provide enough gravitational attraction. The second reason was galactic rotation curves. The standard Newtonian dynamics state that the velocity of stars falls as one move from near the center of mass of a galaxy to its outer edges. However, the 1960 Andromeda galaxy study by Vera Rubin and Kent Ford discovered that the velocity of its stars remained approximately constant despite increased distance from the galactic center (Cain, n.d). This explanation thus leads to a conclusion that the mass of the galaxy should not be entirely defined by the objects that could be seen by telescopes again implying the existence of dark matter. The third reason is the cosmic microwave background. The Cosmic Microwave Background (CMB) describes the earliest photograph of the universe. The patterns seen in observations of the photograph were set up by competition between two forces acting on the matter, namely the force of gravity causing matter to fall inward, and the outward pressure exerted by photons (or particles of light). The competition led to the oscillation of photons and matter into and out of dense regions. If the universe was purely made up of dark matter and normal matter, the pattern would get affected dramatically. The fourth reason is the bullet cluster. The bullet cluster is an object comprising two galaxy clusters that have recently undergone a high-speed collision, forcing the contents of each cluster to merge. In 2006, it was photographic by astronomers working on the Hubble Space Telescope and the Chandra X-ray Observatory. Observations from the two telescopes enabled measurement of the location of the cluster mass after the collision by use of two approaches, namely optical observations of X-ray emission and gravitational lensing (Bahcall, John, Tsvi Piran, and Steven Weinberg, 115). The optical observations of the location of the mass and the location calculated from gravitational lensing showed a glaring inconsistency, rather than overlapping in the bullet cluster if it comprised of ordinary matter.

The fifth reason given by Siegel was large-scale structure formation. Telescopes such as Sloan Digital Sky Survey map locations of the galaxies in the Universe, with the biggest features being called massive structure, in which a set of patterns are seen that couldn’t happen with only gravity because of ordinary matter at work. The structure observed is advanced in its evolution considering the time available for objects to gravitationally collapse after the time of cosmic microwave background. This aspect can only be explained by dark matter, as it didn’t undergo dynamic oscillations with matter and light, and is therefore free to collapse to form dense regions. Dark matter assisted structure formation, giving it a head start and allowing the distribution of galaxies and clusters to become what is observed today (Siegel, n.d).

Properties of dark matter

A) Optically Dark (Dissipationless):

The particles of dark matter must have weak electromagnetic interactions because dark matter is not observed to shine. The electric charge, as well as the electric and magnetic dipole moments of dark matter, must either vanish or the particles are massive. A significant consequence of this property of dark matter is that it cannot cool by radiating photons and hence it will not collapse to the center of galaxies like the baryons that radiate their energy away electromagnetically. This property is also said to be nearly dissipationless.

B) Collisionless:

Dark matter must not interact with light matter to ensure that energy does not get dissipated, and must therefore be nearly collisionless. Dark matter does not collide with any ordinary matter within the galaxies or in the universe, or absorb energy from it, and neither can it be seen or detected using any types of equipment created so far by scientists. This property of dark matter that it neither absorbs nor emits light, explains its name. Astronomers cannot, therefore, observe dark matter directly, but they strongly support its existence based on its gravitational effects. For instance, scientists say that the rapid rotation of galaxies cannot be explained by any "normal" matter within the galaxies; hence the reason to suspect dark matter exists (Wall, Mike, n.d).

C) Cold:

Cold dark matter provided explanations of the observed properties of galaxies in the early 1980's. The measured two-point correlation function of galaxies has indicated that there is a huge amount of power on small scales of power. The small-scale power gets erased when the particles of dark matter have significant velocities. To prevent this occurrence, the dark matter particles must be adequately non-relativistic in the early universe, at the epoch of matter-radiation equality, when the mean temperature of the universe was approximately 1 eV. The limitation in practice is that a particle species in thermal equilibrium must have a mass greater than one KeV. however, a non-thermal species can have smaller mass. The non-thermal production of dark matter can also be realized through late decays of a scalar field. A decay of long-lived particles leads to a non-thermal production of a candidate for dark matter, namely wino, a supersymmetric particle. For a neutral particle to be a candidate for dark matter, the mass of wino should be approximately 2 to 3 TeV.

D) Fluid:

The dark matter must be very fine on galactic scales in such a manner that its discreteness has not been detectable yet. This property of dark matter is associated with two basic effects. The first effect is that the granularity of dark matter provides a time-dependent gravitational potential that may disrupt bound systems. The effect would heat the galactic disk to observable levels for systems of about $10^6 M_\odot$ (solar mass), while smaller systems of about $10^3 M_\odot$, such as globular clusters, would become disrupted. The second effect is that the discreteness of dark matter introduces Poisson noise in the power spectrum of density fluctuations that opposes the observations of the Lyα forest when the particles are massive as compared to approximately m $\geq 10^{4} M_\odot$ (the mass of the sun). Gravitational microlensing places further constraints on dark matter in the solar mass range (Baltz, Edward, 2004). Therefore, it is determined that an upper bound on the dark matter particles' mass of about $m \leq 10^{3\text{-}4} M_\odot \sim 10^{70\text{-}71}$ eV.

E) Classical :

Dark matter must behave in a classical way to be confined on galaxy scales. Bounds can be placed on the masses of both bosons and fermions which they based only on the observed properties of galaxies. The properties of galaxies are that their densities must reach the of order GeV cm^{-3}, so that their velocity dispersions are of order 100 km s^{-1} and that their sizes are of order kpc (1 kpc equals to 3260 light years) (Baltz, Edward A, 2).

Bosons: If dark matter contains bosons, their quantum nature is manifest only when their mass is exceedingly small. Dark matter must be confined on kpc scales to allow for the formation of galaxies. The de Broglic wavelength of the particles with typical galactic velocities is $\lambda \sim$ (eV/m) mm (mass in eV/c^2). To set this wavelength to 1 kpc, it is determined that the particles with mass $m \sim 10^{-22}$ eV/c^2 are barely confined, and this mass denotes the lower end of the possible range of dark matter.

Fermions: The lower bound on the mass of the fermionic dark matter particle is much more stringent when compared to that of bosons. The phase space density of fermions has a maximum value $f = gh^{-3}$, g represents the number of internal degrees of freedom and the value is half from a relativistic gas of fermions in thermal equilibrium.

Possible candidates for dark matter

A) The weakly interacting massive particle or WIMP:

The WIMP is a hypothetical particle that looks promising. The WIMP would be completely different from "normal" matter and would not interact through the electromagnetic force, explaining why they are largely invisible in space. In every second, it is estimate that approximately 100, 000 of these particles pass through every square centimeter of the Earth, interacting only through the weak force and gravity with surrounding matter. If WIMPs exist, there is evidence by mathematical modeling that there are five times more as compared to normal matter, which is a coincidence with the abundance of dark matter that is observed in the universe. Therefore, WIMPs should be able to be detected through collisions as it would result in the recoiling of the charged particles on Earth, producing light that can be observed in experiments that include XENON100. The collision velocity of WIMPS on the set-up would get modulated because of the Earth's motion in the galactic halo. WIMPs make up the halo and they must be drifting through the Earth all the time, and in some occasions, one WIMP will bump into an atomic nucleus. If a WIMP hits a germanium nucleus, the recoiling nucleus heats up the crystal and ionizes hundreds of atoms.

B) The axion:

Axions that are considered as candidates for dark matter refers to low-mass, slow moving particles that do not have a charge and only interact with other matter in a weak way, thus making them difficult to detect, although not entirely impossible. Only axions of a particular mass can explain the invisible nature of dark matter since if they were any lighter or heavier, they would be seen. If axions exist, they should be able to decay into a pair of light particles (photons) that means they can be detected by looking for these pairs. Experiments such as the Axion Dark Matter Experiment are being conducted to detect axions by looking for the pair of light particles. (Ashfaque, Johar, n.d).

Axion production is non-thermal; hence they are cold despite their masses being below the ~ keV limit for warm dark matter. The production of axions relies on the constant coupling of axion-photon that characterizes the interaction between photons and axions (University of Granada, n.d). The preliminary analysis set the limit on axion-photon coupling constant to be $g_{\alpha\gamma\gamma}$ $<6.4\sim 9.6 \times 10^{-10} * \mathrm{GeV}^{-1}$ for the axion mass of $0.05 < m_{\alpha} < 0.26$ eV at 95% confidence level from the absence of the axion signal.

C) The massive astrophysical compact halo object (MACHO):

Macho is believed to be the first candidate to be proposed for dark matter. These objects are composed of ordinary matter, and include neutron stars, and brown and white dwarfs. Although these objects are composed of ordinary matter, they are invisible because they emit very little or no light. MACHOs are observed by monitoring the brightness of distant stars.

As light rays bend when they approach or hit a massive object, light from a distant sources gets focused by a closer object to produce a sudden brightening of the distant object. This effect is known as gravitational lensing and is dependent on the amount of normal and dark matter in a galaxy, as it can be utilized to calculate the amount of matter lurking around.

Based on internal dynamics as well as velocity dispersions of groups of dwarf galaxies, dwarf spheroidal (dSph) galaxies occupy the least massive known dark matter halos in the universe (Shaya, Edward, et al. 5). dSph systems are the least-massive known galaxies. They exist at key position in the hierarchy of spheroidal stellar systems. The dwarf spheroidals are unique as they can probe the particle nature of dark matter.

D) The Kaluza-Klein particle:

The Kaluza-Klein theory was developed around the existence of an invisible ‘fifth dimension’ curled up in space together with three spatial dimensions (namely height, width, and depth), and time. The Kaluza-Klein theory, a precursor to string theory, makes the prediction that the existence of any particle that could be a dark matter particle would have a mass equal to 550 to 650 protons (these make up the atomic nucleus together with neutrons). This dark matter particle can interact through electromagnetism and gravity. However, the particle cannot be observed by looking at the sky as it is curled up in a dimension that cannot be seen. The particle, however, decays into other particles (into neutrinos and photons) that can be measured; hence, should be easy to look for in experiments. The particle has not yet been observed in powerful particle accelerators such as the Large Hadron Collider.

Neutrinos are another possible element of the cosmological dark matter. Neutrino oscillation experiments for atmospheric neutrinos and solar neutrinos have indicated that at least two of the neutrinos in the Standard Model are massive.

E) The gravitino:

The existence of the particle called the gravitino has been predicted by theories that combine general relativity and supersymmetry. Supersymmetry is a successful theory that explains numerous observations in physics and states that all boson particles including the photon (light particle), have a superpartner, with a property known as spin (a type of angular momentum) that is different by a half-integer. The gravitino would be the superpartner of the hypothetical graviton that is thought to mediate the force of gravitation. The superpartner of the graviton, the spin 3/2 gravitino is considered as the first SUSY particle candidate for dark matter. In the models where the gravitino is the lightest superpartner, it is often quite light (keV) and would thus be warm dark matter.

F) Primordial Black Holes:

Primordial black holes form in the early universe under the right conditions that exist when pre-existing adiabatic density fluctuations enter the cosmological horizon and recollapse. The production is increased during periods where the equation of state softens ($p < \rho/3$), such as during a first order phase transition. If the pressure support lessens, objects collapse in an easier way and could more easily form black holes.

G) Branons:

String theory naturally contains objects of different dimensions, referred to as branes. The branes would naturally have fluctuations characterizable as particles that are known as branons. These fluctuations can be made into cold dark matter candidates, both thermal and non-thermal.

H) Mirror Matter:

The concept of a mirror world extends back to the non-conservation of parity in weak interactions. The dark matter in a mirror scenario could just be 'normal' matter in the mirror world, where the only communication with normal matter is gravitational.

Dark matter experiments

A) Dark matter (DAMA) experiment:

A remarkable experiment referred to as Dark Matter (DAMA) is well known for using three styles of detectors to facilitate discovering of WIMPs. The experiment is designed in an exactly similar manner to experiments used in detecting and in the study of neutrinos (Cerulli, et. al., 2017). However, DAMA is designed to look for a specific reaction. DAMA is designed to find the energy generated because of an interaction with a particular element at a particular angle.

The DAMA experiment has three phases, including two research and development (R&D) setups as well as one actual experiment that considers the results of the R&D. The basic idea behind the DAMA experiment is that since the galaxy rotates at a high speed of 232 km/s, the rotation enhances sweeping past the residual Cold Dark Matter (CDM) material. The study involving the reaction of particles ensures the high possibility of using experiment results to detect the WIMP contents of CDM. The phases are as explained below.

Phase one:

The first phase uses Adhesive silicone, CaF_4, which is designed to look for a 2β decay. CaF_4 describes a one component silicone elastomer that cures at room temperature and has good mechanical properties, good heat stability as well as high dielectric properties. The experiment is designed in that format to eliminate known leptons. The phase 1 experiment is set with the intention of determining signs of WIMP detection (Cerulli, et. al., 2017). When the expected results are successful, the second phase is designed as follows:

Phase two**:**

The second phase makes use of isotope of xenon Xe^{129}, which is used since it has a high sensitivity that facilitates research and development. Its superiority allows identifying three WIMP particles, which include photinos, higgsinos, and Majorana Neutrinos (Cerulli, et. al., 2017). After successful results are obtained through detection, the session opens for phase three, which involves the actual experiment.

Phase three:

LIBRA – Large Sodium Iodine Bulk for Rare processes

The Sodium Iodine (NaI) detectors experiment is set up after the two R&D phases. The results obtained should reveal that the experiment determines the presence of particles that display characteristics that qualify particles to be WIMP's (Cerulli, et. al., 2017).

The DAMA project is a project designed to definitively determine the existence of particles that resemble the requirements of WIMP's. The results obtained from the DAMA experiment reveal characteristics of particles such as mirror symmetry, which is a theory of particle physics. If as indicated from theoreticians, it is true that every particle of matter has a mirror particle, this experiment reveals that mirror matter particles consist of only the Cold Dark Matter (CDM) (Cerulli, et. al., 2017).

A. LUX Experiment:

The Large Underground Xenon (LUX) is a dark matter experiment, which is designed to operate underground beneath a mile of rock. It located in Sanford Underground Research Facility in the Black Hills of South Dakota (Chapman, et al., 2013). The LUX experiment is designed to look for dark matter referred to as weakly interacting massive particles (WIMPs). WIMPs are considered as the leading theoretical candidate for dark matter particles. The LUX detectors are composed of a third of a ton of cooled liquid xenon. It is usually surrounded by powerful sensors which are designed basically for detecting minute flashes of light (Chapman, et al., 2013). They also detect the electrical charges emitted in case a WIMP particle collides with a xenon atom within the reaction chamber or tank. The detectors are specifically located at Sanford

Lab underground one mile of rock. It is usually found inside a 72,000-gallon high-purity water tank. The configuration and setup help in shielding it from dangerous cosmic rays as well as effects of other radiation that can easily interfere with a dark matter signals. Scientists make use of calibration techniques using neutrons as stand-ins for managing and controlling WIMPs particles (Chapman, et al., 2013). The effect is achieved through firing a beam of neutrons in the detectors. In this way, scientists gain capability of carefully quantifying the process in which LUX detectors respond to the signals produced from a WIMP collision (Chapman, et al., 2013). Other forms of calibration techniques applied include injecting radioactive gasses inside the detecting chamber to help in distinguishing between signals produced from ambient radioactivity in contrast to a potential dark matter signal.

Do the current detection results (even null results) rule out any of the suggested dark matter candidates?

From the Dark Matter Experiment (DAMA) and the Large Underground Xenon (LUX) experiment, four dark matter candidates from those suggested in previous experiments can be ruled out. These four include the Axion, Neutralino, Gravitino, and Kaluza-Klein particles. This does not mean that they are not possible dark matter particles, but only that they cannot be determined using the experiments above. Some of these candidates are based on theories that cannot be verified. These two experiments are very useful in detecting dark matter in the universe based on some parameters that will be addressed in the second section (Trowland, Lewis, & Bland-Hawthorn, 2012). DAMA and LUX are universally recognized experiments that are used for detecting ideal dark matter particles. Those that are not included in the results can still be detected using other means, but in this analysis, the ones that are being focused on are those that do not fit into the results of the Dark Matter and LUX experiments.

A. Axion:

The axion is said to be a hypothetical elementary particle that was originally postulated to solve the "strong CP problem" (Feng, 2010). Why this suggested candidate can be ruled out by the results of the two experiments is that it does not meet the parameters in the experiments. Axions can only be detected using the Axion Dark Matter Experiment (ADMX) that makes use of a resonant microwave cavity in a large superconducting magnet to look for cold dark matter axions that may be present in the local galactic dark matter halo (Bergström, 2009). The LUX experiment is useful in detecting the dark matter particles that penetrate deep underground, but the axions do not penetrate deep underground, as is the case with most ideal dark matter particles. Also, the Dark Matter and the LUX experiments show results for lightweight particles, but a supercomputer calculation has suggested that the hypothesized axions particle is heavier than thought, and thus cannot fit into the results of the two experiments.

The result of the supercomputer experiment demonstrates that the axions, if they exist, could be not less than ten times heavier than previously thought. If this is true, it could provide a useful clue on how to find it. However, this result also suggests that an experiment that for a long time has been hunting the axions might fail to find it since the detector is designed to look for a lighter version. According to Trowland, Lewis, and Bland-Hawthorn (2012), the issue of mass is a useful parameter that is used to determine the dark matter candidates, and many of them have been known to be of small mass, which is why the two experiments mentioned earlier also detect dark matter particles of small mass. Some researchers also think that the axions might be a component of dark energy – the invisible stuff which is thought to make up almost 85 percent of the Universe's mass (Thomas et al., 2009).

B. Neutralino:

It is worthy to note that the DAMA and the LUX experimental results only list the candidates that meet the principles of direct matter detection. Direct detection is the identification of new particles that may be responsible for the dark matter in the galaxy. Since the neutralino cannot be detected using the direct detection technique, this means that it does not display any of the properties that the other dark matter particles display that can be detected by the direct detection method (Kosmas et al., 2015). This implies that the neutralino does not show any visible collisions with the atomic nuclei, does not display elastic scattering, and does not result in low-energy recoiling of the nucleus. The neutralino does not have any signatures that can make it easy for direct detection.

There are various detection signatures usually displayed by the dark matter particles being detected using the direct detection technique. These signatures include: single scatter nuclear recoils, a dependence on the target material, an exponential shape of the energy spectrum, and the earth's speed that is relative to the galactic rest frame, which is largest in summer. The indirect dark matter detection can be a useful experiment to detect the neutralinos. This is the detection based on their effect when interacting with other particles. The neutralinos are present in the constrained minimal supersymmetric standard model (MSSM) with a conserved R-parity and are expected to annihilate, thereby producing gamma rays (Kosmas et al., 2015). Neutralinos may decay, and annihilation can result in more than gamma rays, with positrons or antiprotons emanating from regions with high dark matter density. Detecting such signals cannot give a conclusive evidence for the existence of dark matter because the production of gamma rays from alternative sources has not been fully understood.

C.Gravitino:

The gravitino has spin-3/2 field, which is a super partner to the spin-1 graviton. There are also reasons why this type of candidate can be ruled out of the suggested dark matter candidates. For one, their interaction is suppressed by a large factor, something that makes it difficult detecting them with the direct dark matter detection technique. The masses of the other dark matters particles range from 10eV to around 1000eV, but with gravitinos, their masses can range from hundreds of eVs to TeVs, thus making it challenging to detect them easily (Grefe, 2011). Also, they have extremely weak coupling, meaning that they are inaccessible to direct as well as to indirect searches. Additionally, their direct production at colliders is highly suppressed for masses not less than 0.1keV, because of extremely weak coupling. The presence of the gravitinos in the particle spectrum results in numerous cosmological problems, of which the most severe is that late decays of gravitinos conflict with the fruitful predictions of primordial nucleosynthesis, which is responsible for the abundances of light elements (Feng, 2010). The fact that gravitinos are theoretically produced in thermal scatterings at the end of the inflationary stage in the early universe, means that their compatibility with big bang nucleosynthesis would put intense upper restrictions on the universe's reheating temperature. However, the detection of small and non-vanishing neutrino masses supports the idea of thermal leptogenesis as the basis for the universe's baryon asymmetry, thereby requiring a high reheating temperature value. Because of that reason, there is an obvious conflict between supersymmetry, the prediction of the formation of gravitinos, and predictions of big bang nucleosynthesis as a technique for baryogenesis.

B. Kaluza-Klein Particles:

The Kaluza-Klein particles arise from the extra dimensions of the Standard Model SM particles that propagate in higher dimensional bulk, which are the universal extra dimensions (Thomas et al., 2009). This is the fourth candidate that can be ruled out by the results of the DAMA and the LUX experimental results. For one, they do not contain a signature that can be detected by the direct detection mechanism, like the other candidates. Since the Kaluza-Klein particles are of different sizes, it is only the smallest particles that match the parameter regimes for the DAMA and LUX results because they resemble the WIMPS, which are the perfect example of dark matter particles that are detectable using the direct detection technique.

If certain candidates are not ruled out, what are the dark matter parameter boundaries established by current detector results?

A. UV Boundary and Thermal Constraints:

The renormalization group can be used to constrain the gauge as well as the scalar sector couplings to reduce the parameter space of a detector model. This means the SM Higgs quartic coupling (including other scalar couplings) should reach a fixed point at a particular UV scale, △UV (△ denotes a change), to ensure there is asymptotic safety in the scalar sector, thereby providing certain UV boundary conditions besides generating a stable Higgs vacuum. The scheme of renormalization defines the renormalization constants (in the Higgs model equation), such as their finite part. The renormalization group, on the other hand, states that there is no scheme dependence of the physical observables. The Higgs mechanism is part of the standard model used to explain the masses of spontaneous particles that are interacting in each magnetic scalar field. These boundary conditions help to solve renormalization group equations as the resulting couplings of the electroweak scale are highlighted (Wang et al., 2015).

If dark matter is thermally produced just like in the case of the WIMP paradigm, its abundance can be governed by a rate equation that is simplified using the analytic Lee-Weinberg approximation. The solution of the rate equation and insertion of the observed dark matter abundance creates a restriction on the cross section of the thermally averaged annihilation. The solution comes from the equation calculating the abundance of dark matter particles, interacting in each mass of bosons (photons or elementary particles) in an electromagnetic field wherein the dark matter is suspected to be present.

We can then compare the constrained cross section against the cross section calculated by the gauge coupling values that were computed from the ultra-violet (UV) boundary conditions to limit the mass range of the detector or model to a handful of points (Sage et al., 2016). The masses read from the points where the curves intersect the abundance constraint forms the mass values that are acceptable for cold dark matter.

B. Density Parameter Boundaries:

The Lambda CDM (cold dark matter) model, which is the standard model of cosmology, holds that the current CDM density parameter is $\Omega c=0.2589\pm0.0057$ kg/m^3. Therefore, based on the cosmological standard model, cold dark matter makes up about 80 percent of the current matterdensity. Dark matter need not be perfectly correlated with baryonic matter; therefore, there is not necessarily an issue to have systems consisting mostly of baryons or CDM (Trowland, Lewis, & Bland-Hawthorn, 2012). It should also be understood that the CDM density parameter stated above is not a constant throughout the history of the universe. It is the current value of density, that is, its value right now according to the DAMA and the LUX experimental results.

There are four components of the matter-energy density of the universe, and these include the dark-energy density, the matter density, the baryon density, and the luminous baryon density. All matter and energy has a total matter density fraction (compared to the critical density required for a “flat” geometry of the universe) that does not exceed 1.00, matter density (dark matter) not exceeding 0.31, baryon density not exceeding 0.045, and luminous baryon density not exceeding 0.005 (Thomas et al., 2009). To comprise the rest of the density fraction, dark energy has postulated.

C. Scalar Spectral Index:

The scalar spectral index is another useful parameter that is used by the dark matter detectors. It describes how density changes or fluctuations vary with scale. The Wilkinson microwave anisotropy probe measured the power spectrum of the CMB (cosmic microwave background) for multipoles with unprecedented accuracy. A combination of the CMB findings with other astrophysical observations has resulted in strong constraints on the accepted cosmological parameters like the Hubble parameter, baryon density, and the age of the universe

(Lidsey&Tavakol, 2003). The power spectrum of the primordial fluctuations provides constraints to differentiate between the several inflationary models. A Taylor series in this case is a series expansion of a function at a given point. This is a useful parameter that is used for constraining ideal dark matter. An index of unity denotes similar variations on all the scales. Input parameters of the Lambda CDM influences the size-scales of structure formation. The earlier inflation models (it's a kind of model of structure formation) do suggest some values that are compatible with the current inflation models**.**

D. Reionization Optical Depth:

The Big Bang Theory and cosmology refer to the reionization of the matter in the universe after the lapse of the dark ages. Cosmic reionization, as well as dark matter decay, can affect the observations of the cosmic microwave sky in the same way. A simultaneous study can be done for both cases to constrain unstable dark matter from the cosmic microwave background observations. Two reionization models are compared with and without dark matter decay. Planck 2015 data is leveraged to constrain the rate of effective decay of dark matter to $t_{eff} < 2.9 \times 10^{-25}$/s at 95 percent CL (Liu, Slatyer, & Zavala, 2016). This limit is robust as well as model independent. It also holds for any decaying dark matter as it relies only weakly on the selected parameterization of astrophysical reionization.

If current detectors seem unsuccessful in being able to detect dark matter particles, what new detector capabilities are expected to be needed for next-generation studies?

The density of normal matter is very high in the earth, a situation that causes dark matter to evade detectors. However, in environments such as the vacuum of space, the matter density is tiny and the fields present have the capability of driving dark matter for easier detection. Current detectors that have been used have failed to detect dark matter because normal matter has a too high density (Lawrence, 2015). However, recent proposals suggested that an atomic interferometer designed to operate within microscopic scales can be used to search dark matter components (Brown University, 2016). The proposed equipment should consist of ultra-high vacuum materials fitted within vacuum chambers. The chambers should have few individual atoms in a design to produce a low-density environment, such as in space, to reduce dark matter screening. Through experiments performed by dropping Cesium atoms above aluminum, it was revealed that sensitive lasers could be applied in determining forces of falling atoms (Lawrence, 2015). The forces that could affect the atoms included only the gravitational force, and therefore the set-up eliminated forces that would cause atoms to separate and move away from detectors. The teams are focusing on applying such innovative techniques to help in determining dark matter particles in the future experiments.

What new detectors are currently being designed and built and what improvements in identifying dark matter properties will they have?

Initially, the Large Underground Xenon detector (LUX) was known to be the most sensitive detector for hunting dark matter components. However, there were still several unseen and undetected dark matter candidates, which accounted for most dark matter. Among the undetected particles are included weakly interactive massive particles (WIMP), which and are considered as leading components of dark matter (Brown University, 2016). The evidence that shows dark matter manifests the effects of gravity is observed during rotation of galaxies, and due to the bending of light as it travels through the universe. WIMPs have not been detected since they rarely interact with other particles. Scientists are focusing on applying what has been learned by LUX. Therefore, scientists are designing a new detector with the intention of improving the sensitivity of LUX by a factor of more than 20 times for low mass dark matter particles (Lawrence, 2015). Designers are pushing their efforts so that the capabilities of detectors can be higher to search for elusive dark matter particles.

Among the experiments aiming at direct detection of WIMPs included LUX-ZEPLIN, (LZ) which will replace LUX. New improvements include replacing 1.3 tons' liquid xenon with 10 tons' liquid xenon (Brown University, 2016). New calibrations included in the system will use neutrons as stand-ins for dark matter particles. Another technique includes bouncing neutrons away from xenon atoms for effective and efficient quantifying the response of the detector through the recoiling process. Scientists are planning to increasing sensitivity of LUX-ZEPLIN (LZ) to be over 100 times higher than that of LUX (Lawrence, 2015). The LUX-ZEPLIN (LZ) is designed such that it shall have enough sensitivity to detect the type of neutrinos originating from the sun. The proposed technology will be launched by 2020.

Conclusion

Dark matter is the unseen mass or material that scientists have postulated to exist in the universe. Siegel gave various reasons for postulating the existence of dark matter, namely galaxy clusters, galactic rotation curves, the cosmic microwave background, the bullet cluster and the large-scale structure formation. Dark matter has several properties that include being optically dark (dissipationless), collisionless, cold, fluid and classical. The possible candidates for dark matter in the universe include the weakly interacting massive particle or WIMP, the axion, the Massive Astrophysical Compact Halo Object (MACHO), the Kaluza-Klein particle, the gravitino, Primordial Black Holes, Branons and Mirror Matter. Two experiments have been discussed for looking for dark matter, namely the Dark Matter (DAMA) experiment and The Large Underground Xenon experiment (LUX). The DAMA experiment is a remarkable experiment that uses three styles of detectors to facilitate discovering of WIMPs. The LUX has been identified as a sensitive device for looking for dark matter. LUX is based on cooled liquid Xenon, surrounded by water in a stainless-steel tank located nearly a mile underground.

Dark matter makes up a quarter of the mass-energy density of the universe. To detect the existence of this matter there are some experiments which have been used. A map of dark matter in the universe has been created to show how light is distorted by galaxy clusters. One would ask why we cannot see the dark matter. This is because it does not interact with regular matter in any way. Other states of matter collide and absorb energy, while the dark matter does not. It is existence can only be inferred because we see the effects of its existence on visible objects. Caution should be taken not to confuse antimatter with dark matter. Antimatter behaves in all ways like matter but the difference is that it has electrical charges opposite to that of matter. A positron is positively charged and is the anti-particle of the electron. Negative matter is a type of hypothetical matter which would contain negative mass and energy. It contains negative gravitational charge and repels normal matter.

Dark matter can be assumed to be the building blocks of the galaxies and clusters. Axions can be detected by using the axion dark matter experiment that makes use of a resonant microwave cavity in a large superconducting matter to look for cold dark matter axions that may be present in the local galactic halo. The Neutralino does not show any visible collisions with the atomic nucleus, display elastic scattering, display low energy in the recoiling nucleus and does not have any signatures that make it easy for detection. Gravitinos have weak coupling which make them inaccessible for direct and indirect searches. Some of the dark matter parameters established by current detectors include: UV and thermal constraints, density parameter boundaries, mass parameter boundaries, scalar spectral index and re ionization optical depth. In conclusion, improvements have been made to the detectors such as new calibrations, the use of 10 tons of liquid xenon and the use of bouncing neutrons away from xenon atoms for efficient quantifying of the detector through the recoiling process.

Overall, I anticipate that in the future there will be additional discoveries to gain more information about dark matter, allowing scientists around the world to become more familiar with the properties of dark matter, a major component of our universe.

References

1. Ashfaque, Johar. Here are the top five candidates for 'dark matter' Web. December 14, 2015. Retrieved from http://www.sciencealert.com/from-machos-to-wimps-meet-the-top-five-candidates-for-dark-matter

2. Baltz, Edward A. "Dark matter candidates." *arXiv preprint astro-ph/0412170* (2004): p. 1-14

3. Bahcall, John, Tsvi Piran, and Steven Weinberg. "Dark matter in the universe." Dark Matter in the Universe: Jerusalem Winter School for Theoretical Physics. 2004. 108-133.

4. Bergström, L. (2009). Dark matter candidates. *New Journal of Physics*, *11*(10), 105006.

5. Brown University (2016). World's most sensitive dark matter detector completes search. Retrieved from: https://phys.org/news/2016-07-world-sensitive-dark-detector.html

6. Cain, Fraser. How do we know dark matter exists? Universe Today. Web. March 13, 2015. Retrieved from https://phys.org/news/2015-03-dark.html

7. Cain, Fraser. How Do We Know Dark Matter Exists? December 23, 2015. Universe Today. Web. Retrieved from http://www.universetoday.com/119297/how-do-we-know-dark-matter-exists/

8. Cerulli, R., Villar, P., Cappella, F., Bernabei, R., Belli, P., Incicchitti, A., Addazi, A., ... Berezhiani, Z. (2017). DAMA annual modulation and mirror Dark Matter. *The European Physical Journal C: Particles and Fields, 77,* 2, 1-20.

9. Chapman, J. J., Faham, C. H., Fiorucci, S., Gaitskell, R. J., Malling, D. C., Pangilinan, M., Verbus, J. R., Pease, E. K. (2013). The Large Underground Xenon (LUX) experiment. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 704,* 111-126.

10. Feng, J. L. (2010). Dark matter candidates from particle physics and methods of detection. *Annual Review of Astronomy and Astrophysics*, *48*, 495-545.

11. Grefe, M. (2011). Unstable gravitino dark matter-Prospects for indirect and direct detection. *arXiv preprint arXiv:1111.6779.*

12. Kosmas, T. S., Miranda, O. G., Papoulias, D. K., Tórtola, M., & Valle, J. W. F. (2015). Sensitivities to neutrino electromagnetic properties at the TEXONO experiment. *Physics Letters B*, *750*, 459-465.

13. Lawrence B. (2015). New results from world's most sensitive dark matter detector. Retrieved from: https://phys.org/news/2015-12-results-world-sensitive-dark-detector.html

14. Lidesey, J., Z, Tarakol. (2003). Running of the scalar spectral index and observational signatures of inflation. https://arxiv.org › astro-ph

15. Liu, H., Slatyer, T. R., & Zavala, J. (2016). Contributions to cosmic reionization from dark matter annihilation and decay. *Physical Review D*, *94*(6), 063507

16. Lopes A. (2017). Synopsis: Self-Interacting Dark Matter Scores Again. Retrieved from: https://physics.aps.org/synopsis-for/10.1103/PhysRevLett.119.111102

17. Sage, F. S., Wang, Z. W., Dick, R., Steele, T. G., & Mann, R. B. (2016). Detection prospects for conformally constrained vector-portal dark matter. *arXiv preprint arXiv:1610.07574*.

18. Shaya, Edward, et al. "Properties of Dark Matter Revealed by Astrometric Measurements of the Milky Way and Local Galaxies." *arXiv preprint arXiv:0902.2835* (2009). P. 1-8

19. Siegel, Ethan. Five Reasons We Think Dark Matter Exists: No other idea explains even two of these. Web. August, 19, 2014. Retrieved from https://medium.com/starts-with-a-bang/five-reasons-we-think-dark-matter-exists-a122bd606ba8#.7oszvjvx8

20. Thomas, J., Saglia, R. P., Bender, R., Thomas, D., Gebhardt, K., Magorrian, J., ... & Wegner, G. (2009). Dark matter scaling relations and the assembly epoch of Coma early-type galaxies. *The Astrophysical Journal*, *691*(1), 770.

21. Trowland, H. E., Lewis, G. F., & Bland-Hawthorn, J. (2012). The cosmic history of the spin of dark matter halos within the large-scale structure. *The Astrophysical Journal*, *762*(2),72.

22. University of Granada. Scientists provide new data on the nature of dark matter. Physical Review Letters. March, 3, 2015. Retrieved from https://phys.org/news/2015-03-scientists-nature-dark.html

23. Wall, Mike. What Is Dark Matter? Prime Candidate Gets Profiled. Web. November 2, 2016. Retrieved from http://www.space.com/34595-dark-matter-search-axion-mass.html