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Investigating the properties of Dark Matter

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Abstract: ***This paper delves into the enigma of dark matter, an invisible yet significant constituent of the universe. Through historical insights, observational support, and theoretical models like the Cold Dark Matter (CDM) and Lambda Cold Dark Matter (ΛCDM) models, it uncovers the gravitational impact of dark matter on cosmic structures. Additionally, the study explores candidates such as Weakly Interacting Massive Particles (WIMPs) and axions, illuminating their potential roles in solving the puzzle of dark matter's elusive nature.***

Keywords: Dark Matter, Observational Evidence, Theoretical Models, WIMPs, Axions

1. Introduction

The Universe, an awe-inspiring expanse of celestial wonders, has captivated human curiosity since time immemorial. However, lurking beyond the shimmering stars and gigantic planets of the universe lies a cosmic enigma that challenges our very understanding of the cosmos. This enigma comes in the form of dark matter and dark energy.

Dark matter is hypothesized to consist of 27% of the universe, yet it defies direct detection (”NASA”, n. d.). In spite of that, its gravitational grip governs the dynamics of the universe. Its presence continues to tantalise researches, prompting them to research more.

Dark Matter is an elusive component of the Universe that defies direct detection. Unlike ordinary matter, it does not emit light nor does it interact with it, making it invisible to observations by astronomers. It may be asked, how do we even know it exists if it cannot be seen. Just because we cannot see it, does not mean that we are unable to detect the effects of it. It's effects can be detected or rather inferred from its gravitational effects on the cosmos, in particular on galaxies and galaxy clusters. In this section, we delve into the historical background and observational evidence that paved the way for the concept of dark matter. We shall then explore the exist ant theoretical models to explain and clarify the nature of dark matter. Finally, we shall aim to understand the significance and impact of dark matter in shaping the Universe.

2. Dark Matter

2.1 Historical Background

The journey to understand the nature of the cosmos, and in particular dark matter may be traced back to the 20th Century. Early speculation on the existence of dark matter started with Lord Kelvin, a prominent scientist in his own right. He used estimates drawn from the observed velocity dispersion of stars, indicating how fast these stars were orbiting around the core of our galaxy, the Milky Way, which allowed him to estimate the mass of our galaxy, as a stronger gravitational pull indicates a greater velocity and thereby a greater mass. However, there was a difference between the calculated mass and the mass of the number of stars we can see or observe, leading him to conclude that “Many of our supposed thousand million stars, perhaps a great majority of them, may be dark bodies”, as per the appendix of his book, ”Baltimore lectures on molecular dynamics and the wave theory of light” (Kelvin, 1904). Next, Henri Poincoir´e, a French Mathematician, referred to the term ”Dark Matter” when making a reference to Lord Kelvin's work (Poincar´e, 1906). He, however, hypothesized that the amount of dark matter in the Universe would have to be significantly less as compared to observable matter, which we know is untrue.

However, the actual breakthrough came when in 1933, astrophysicist Fritz Zwicky was studying Hubble's observations of the Coma Cluster of Galaxies, wherein he noted an anomaly. Zwicky applied the virial theorem to the Coma Cluster of Galaxies. The virial theorem is used to infer the mass of a group of orbiting bodies from the velocity of its components. It gives an equation which relates the total kinetic energy of a self-gravitating body due to the motion of it's parts, which may be observed below.

$$\langle T \rangle = -\frac{1}{2}\sum_{k=1}^{N}\langle \mathbf{F}_k \cdot \mathbf{r}_k \rangle$$

Zwicky observed that according to the amount of visible mass, single galaxies were moving way too rapidly to remain together in a cluster (Zwicky, 1933). He then posited that for the cluster to remain together, there must another type of unobserved dark mass which exerts a gravitational force on the cluster, dubbing it ”Dark Matter. ” Whilst Zwicky's estimates were off, due to the obsolete value of the Hubble's Constant, his concept was correct. Since then, there have been many advents in the progress of our discovery of this concept known as dark matter.

Observational Evidence for Dark Matter

Whilst this may sound ironic, as dark matter is not visible, there is ample observational evidence for the existence of dark matter. Whilst this evidence may also support alternative theories, the existence of dark matter is hitherto the most reliable one.

Galactic Rotation Curves

Perhaps the most influential piece of evidence proving the existence of dark matter comes from studying the rotation curves of spiral galaxies. A rotation curve is a graphical representation of the rotational velocity of objects within a system, such as stars within a galaxy, as a function of their distance from the centre of the system, which in our case would refer to the galaxy. Rotation curves are able to provide crucial insight to astronomers about the distribution of mass in a galaxy (Hammond, 2008). Researches over years have found that whilst measuring the relative velocities of stars in spiral galaxies, the velocity remained constant or increased with the distance from the centre of the galaxy, which was contrary to the principal of celestial mechanics which stated that the majority of the mass of the galaxy rests in a flattened, disk-like structure around the centre of the galaxy.

The behaviour of the rotation curves indicated that there must be another additional mass on the outskirts of the galaxy contributing significantly to the gravitational pull on the stars. According to Kepler’s Laws, starts on the outskirts of the galaxy should move significantly slower as the equation for orbital velocity is:

$$v = \sqrt{(\frac{GM}{r})}$$

Through this equation we may see that the square of the velocity is inversely proportional to the orbital radius ($v_2 \propto 1/r$). However, researches observed that this is not the case, as may be seen in Fig 1.

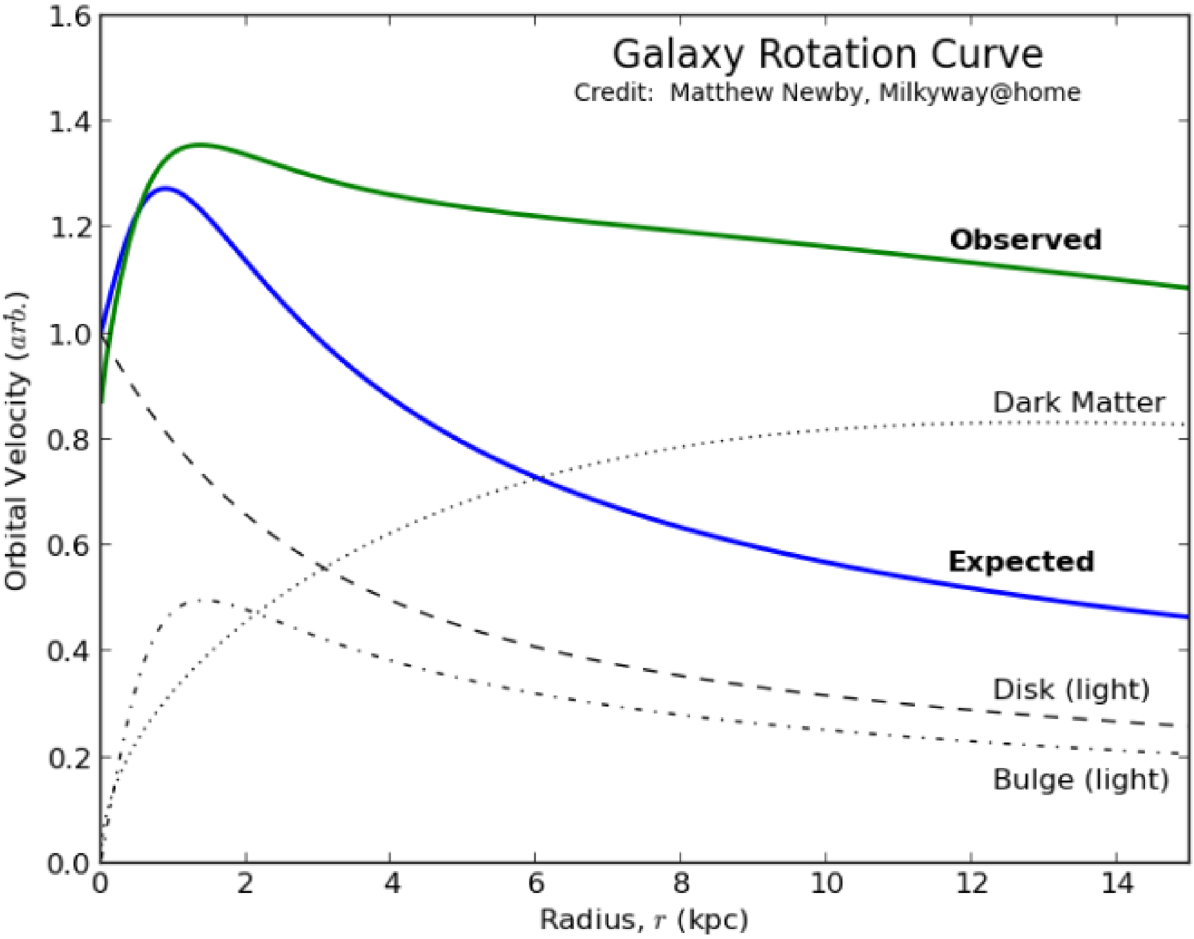

Figure 1: Galaxy Rotation Curve (Newby, n. d.)

This is why they hypothesized that there must be an unseen mass componentin the universe, which was aptly named ”dark matter. ” The presence of dark matter in galaxies indicates the existence of dark matter halos enveloping visible galactic disks, containing a large amount of dark matter.

Gravitational Lensing

Gravitational Lensing is a phenomenon predicted by Albert Einstein’s theory of general relativity which describes how massive objects, such as galaxies and galaxy clusters are able to bend the path of light as it travels through space time (Information [at]eso. org, n. d.). This effect occurs due to the curvature of space time caused by a massive object. The process of gravitational lensing may be more aptly described by Fig **??**. Gravitational lensing provides evidence for the existence of dark matter through its impact on light, even though dark matter does not interact with the electromagnetic field.

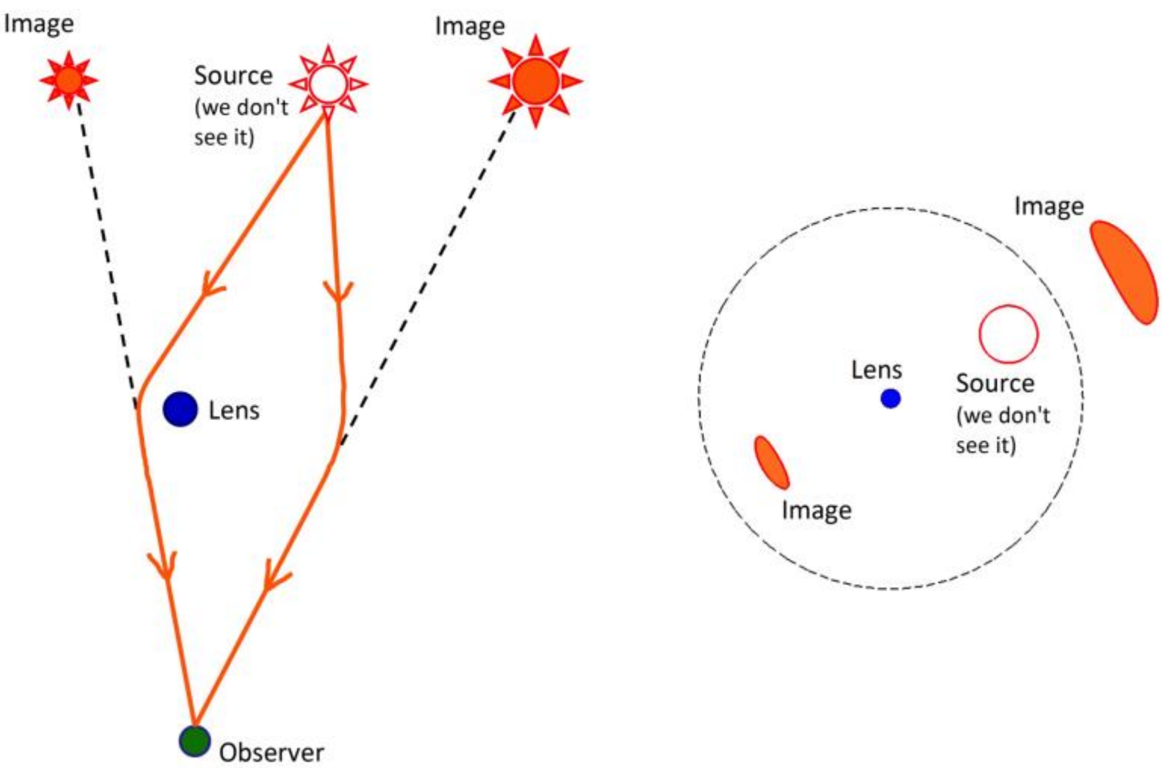

Figure 2: Gravitational Lensing Procedure (Kogan & Tsupko, n. d.)

In regions with high concentrations of mass, for instance galaxy clusters, strong gravitational lensing may occur wherein the gravitational pull of dark matter causes substantial bending of light from background objects such as quasars, as a result of which multiple images of the same background image may appear, forming Einstein Rings around the foreground mass, which has been observed in various distant clusters Abell 1689. By measuring the distortion, the mass of the cluster can be obtained, and the amount of distortion depends on the mass of the cluster and distribution of the mass. The mass-to-light ratios obtained from gravitational lensing relate to the dynamical dark matter measurements of clusters.

Weak gravitational lensing, on the other hand, investigates minute distortions of galaxies (Bartelmann & Maturi, n. d.). In cases where the lensing gravitational effect is not strong enough to create multiple images as seen in strong gravitational lensing; however, by examining the shear deformation of back-ground galaxies and using statistical analyses from vast galaxy surveys, the mean distribution of dark matter in that region can be categorised. It is nec-essary to note that dark matter itself does not bend light, however, it bends spacetime, which in turn bends light.

Cosmic Microwave Background

The cosmic microwave background is leftover or remaining radiation from the Big Bang, and whilst the CMB cannot be observed directly, it is present all throughout the Universe. The CMB dates back to about 380, 000 years after the Big Bang; this is because in the early stages of the Universe, right after the Big Bang, the temperature of the Universe was at about 273 Million Kelvin (Fixsen, 1995). Any atoms that were formed at the time were quickly broken down into subatomic particles and the radiation from the CMB in photons was scattered off the electrons, and as a result, photons wandered through the Universe in its initial stages. After approximately 380, 000 years had past, the Universe was cool enough to ensure that hydrogen could form. As the CMB photons were unaffected by hitting the Hydrogen atoms, they could now travel in straight lines, resulting in a defined Cosmic Microwave Background (CMB).

The cosmic microwave background is another piece of evidence of dark mat-ter. Although both ordinary matter which we interact with, and dark matter, is forms of matter, they do not behave in the same way. This can clearly be seen with the lack of electromagnetic interaction of dark matter whereas ordi-nary matter does. It is for this very reason that we are unable to touch dark matter, though it is said that dark matter does pass through our body in small quantities during our lifetime. In the early stages of the universe, ordinary mat-ter was ionised and as a result highly unstable, and interacted strongly with radiation using Thomson Scattering, a process where charged particles scatter photons due to their electromagnetic interactions. Dark Matter, on the other hand, does not directly interact with the Cosmic Microwave Background. That being said, it does affect the CMB by its gravitational potential (Marques & Huffenberger, 2022). One of the most remarkable features of the CMB is its nearly perfect blackbody radiation spectrum, wherein a blackbody is referred to as an object that emits and absorbs radiation of all wavelengths with a spe-cific temperature dependent distribution. Dark Matter and ordinary matter interact with the CMB differently, allowing scientists to deduce the amount of dark matter present as they leave different imprints on the CMB.

Theoretical Models and Candidates

Whilst we have various aspects of observational evidence that support the exis-tence of dark matter, we have not fully understood the nature of dark matter, and to resolve this mystery, various theoretical models have been designed in order to predict the nature of dark matter.

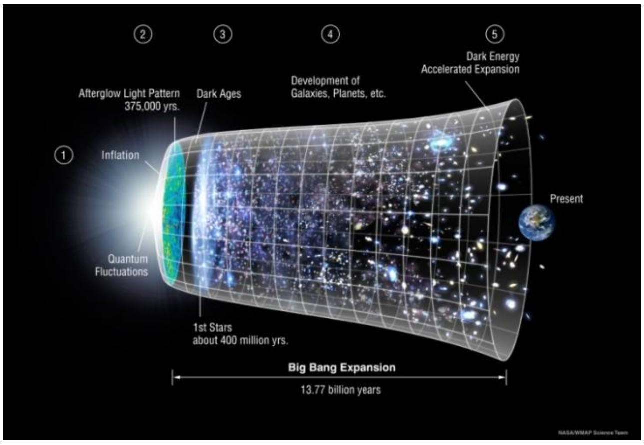

Figure 3: ΛCDM Model of Cosmology (“Figure from NASA / LAMBDA Science Team”, n. d.)

The Cold Dark Matter Model (CDM)

The Cold Dark Matter Model is a theoretical framework that describes the distribution and behaviour of dark matter in the universe. In this model, Dark Matter is assumed to be composed of non-relativistic particles, moving at very low velocities compared to the speed of light at the time of their formation, thus being called cold. These particles primarily interact through gravity and do not experience significant interactions with photons or other forces, as a result of which they can clump together due to their gravitational attraction, allowing the formation of various cosmic structures (Millis, 2020).

Lambda Cold Dark Matter Model (ΛCDM)

The CDM is a model which is an extension of the CDM Model which also incorporates the cosmological constant (Λ) into the equations of general relativity, which represents dark energy. In this model, the cosmological constant (Λ) stands to counteract the gravitational attraction of matter and maintain a static universe, which was the prevailing belief at the time (GaBany, n. d.). This model may concisely be observed in Fig **??**.

This constant of Einstein’s was referred by him as his greatest blunders when Hubble discovered that the Universe is expanding, causing the cosmological constant to be set to 0. However, later it was reintroduced to explain why the universe was not slowing down due to gravity, when observations of cosmic microwave background radiation suggested the Universe was flat and had a critical density.

Weakly Interacting Massive Particles (WIMPs)

WIMPs are arguably the most popular and well studied dark matter candidates. As per this theoretical model, dark matter consists of new elementary particles that weakly interact with ordinary matter and other WIMPs (Conroy et al., 2006). Moreover, they neither emit nor do they absorb light. Upon interaction with each other, however, they annihilate and generate gamma rays. They are hypothesized to be heavy and slow moving, otherwise they would not have clumped together from which galaxies and clusters of galaxies formed (Griest, 1993). WIMP’s are considered to be nonbaryonic particles, or particles that are not baryons, which are a type of particle which contains an odd number of valence quarks. They belong to the type of particles called hadrons, which are composed of quarks. For instance, a proton may be considered to be a baryon as it has 3 quarks, 2 up quarks and 1 down quark (uud) (of Encyclopaedia Britannica, 2023). Although we do not know the precise nature of these particles, as they are not predicted by the standard model of particle physics, there are a few extensions to the current model, including the theory of supersymmetry which predict certain hypothetical elementary particles, which states that these may be undetected WIMP’s. Despite efforts to understand the nature of WIMP’s, it is essential to note that WIMP’s have not been directly detected as of yet.

Axions

Axions are hypothetical elementary particles that were first proposed in the late 1970s by the Peccei-Quinn Theory to resolve the strong CP Problem in Quantum Chromodynamics, the theory that governs the strong nuclear force in an atom. In the context of the standard model of particle physics, which encompasses the known fundamental particles and their interactions, QCD has the potential to generate a term known as the theta (θ) term that violates the combined symmetries of charge conjugation (C) and parity (P), collectively termed CP (’t Hooft, 1976).

Whilst the CP violation is observed in weak interactions, constraints on the electric dipole moments (EDMs) of particles, particularly the neutron, impose stringent limits on the level of CP violation that QCD could cause. This implies that the theta term in QCD, which quantifies the extent of CP violation in the theory, must be exceedingly small. The question arises: Why is this theta parameter so close to zero, given that it could theoretically span the range from 0 to 2π.

To address this issue, Roberto Peccei and Helen Quinn introduced the Peccei-Quinn mechanism, which suggests the existence of a new global symmetry to dynamically resolve the strong CP problem. This symmetry is then later broken spontaneously, resulting in the emergence of a new particle: the axion, which is still purely theoretical.

The Peccei-Quinn mechanism proposes that the theta parameter is not fixed but rather promoted to a dynamical field, associated with the axion. This then offers a solution to the CP Problem by naturally suppressing the effects of CP violation without requiring an unnaturally small value for the theta parame-ter (Peccei & Quinn, 1977). The axion thereby functions as a particle that shares similar properties with a category of particles known as pseudo-Nambu-Goldstone bosons, as these particles too emerge as a result of spontaneous sym-metry breaking. Similarly, the axion is also associated with a concept analogous to the Higgs Boson’s connection with the Higgs field; this connection may be drawn from the introduction of a new type of symmetry known as the the global symmetry, leading to the manifestation of the axion as a particle when that symmetry undergoes breakage.

Axions dark matter composes an intriguing solution to two of the physic’s problems, the nature of dark matter itself as well as the strong CP Problem. Arising from the implications of QCD, it has been hypothesized that axions interact with an effective periodic potential due to QCD effects, giving rise to the axion field's oscillations, which is known as malignant mechanism, which generates a population of cold axions during the earliest moments of the Uni-verse, depending on the mass of the axion. If the mass of an axion exceeds a certain threshold of (around 5*eV/c* or 10−11 times the electron's mass), they could account for the dark matter in our Universe, whilst addressing the strong CP Problem (di Luzio et al., 2020). If inflation occurred with modest energy levels and persisted for a significant period, the axion's mass could reach values as low as 1 peV/c^2, emphasizing the intricate relationship between cosmological phenomena and particle properties. In the context of different conditions surrounding the spontaneous breaking of the Peccei-Quinn (PQ) symmetry-responsible for the axion's emergence-two distinctive scenarios are outlined:

1) **Pre-inflationary scenario:** When the PQ symmetry breaking aligns with both the inflation period and the post inflation Universe conditions, a uniform initial axion field value is selected during cosmic inflation. In this scenario, we eliminate the topological defects as they do not contribute to the axion energy density.
2) **Post-inflationary scenario:** If any of the two conditions are broken, which is the PQ symmetry is spontaneously broken during inflation or the PQ symmetry is never restored after its spontaneous breaking occurs, the axion field takes different values in causally disconnected regions of the Universe. These re-gions are separated by domain walls, which are unstable and decay into axions. The axions produced by the domain wall decay have a large initial velocity dis-persion, which affects their clustering properties and their detection prospects. Additionally, cosmic strings may form at the PQ phase transition and act as sources of axion radiation. The contribution of strings to the axion energy density depends on the string tension and the axion decay constant.

3. Conclusion

In conclusion, dark matter, though elusive, asserts its presence through gravitational influences on cosmic structures. The exploration of galactic rotations, gravitational lensing, and the cosmic microwave background unveils its impact. Theoretical constructs, including axions, offer potential explanations while raising further questions about particle properties and interactions.

The quest for dark matter's identity continues to challenge the frontiers of particle physics and cosmology. Experimental endeavors, spanning underground detectors and astrophysical observations, strive to detect its elusive particles and elucidate their properties.

As we peer into the future, the quest for dark matter remains a cornerstone of scientific inquiry. Unanswered queries propel us toward a more comprehensive understanding of the universe's underlying dynamics, compelling us to decipher the enigmatic role of dark matter in the intricate interplay of cosmic forces.

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