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REVIEW ARTICLE

The Matter-Antimatter Asymmetry: A Potential Link to Dark Matter

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ABSTRACT: Matter-antimatter asymmetry is one of the biggest mysteries of the early universe. According to quantum field theory, every fundamental particle has a corresponding antiparticle with identical mass and opposite charge. Under high-energy conditions, particle–antiparticle pairs can be created, and when they come into contact, they annihilate, converting their mass into energy. But our universe proves otherwise. We only have tiny amounts of antimatter, whereas everything we observe, from microscopic molecules to humans to giant galaxies, is made of matter. How has ordinary matter not been annihilated by antimatter? Should our universe exist at all? Could there be a link to dark matter, a mysterious substance forming about 27% of our universe? In this review paper, we dive into the matter–antimatter asymmetry and explore whether it could be linked to the nature of dark matter while reviewing current findings, focusing on the Standard Model, the model that best describes the building blocks of the universe, CP [charge conjugation (C), parity (P)] violation, the violation of fundamental symmetries, and data from recent discoveries like the Euclid and Planck missions and CERN experiments. We believe this literature review will help cosmologists uncover the mysteries of dark matter and the matter-antimatter imbalance.

KEYWORDS: Physics and Astronomy, Astronomy and Cosmology, Matter-Antimatter Asymmetry, Dark Matter, CP Violation, Standard Model.

Introduction

The laws of physics as we understand them say that the universe should not exist. That is because of the Standard Model (SM), which is the most accepted theory describing the fundamental particles and forces in nature. It organizes matter into six types of quarks and six leptons, and includes various force-carrying particles (called gauge bosons) that allow these particles to interact with one another.[1, 2] Quarks are the building blocks of protons and neutrons. There are 6 different types (flavors) of quarks: up, down, charm, strange, top, and bottom. They combine and form subatomic particles. Leptons include particles like electrons and neutrinos, whereas the gauge bosons include photons, gluons, and the W and Z bosons, which mediate the electromagnetic, strong, and weak forces. Quarks are the building blocks of protons and neutrons. There are six types, called 'flavors': up, down, charm, strange, top, and bottom. These combine to form subatomic particles. Leptons include electrons and neutrinos, while gauge bosons (such as photons, gluons, and W and Z bosons) mediate the fundamental forces. In short, the Standard Model organizes all known matter and interactions into these fundamental components.[3] Although CPT [charge conjugation (C), parity (P), and time reversal (T)] symmetry ensures symmetric laws for matter and antimatter, the observed imbalance requires mechanisms like CP violation to produce a net matter dominance.[4] In this view, many particles have corresponding antiparticles with opposite charges, which could annihilate each other upon contact, releasing energy. Since we are all made of matter, this annihilation did not completely eliminate matter; some particles survived, leaving behind only tiny amounts of antimatter. This imbalance is one of the biggest mysteries in cosmology. Understanding why matter dominates over antimatter could reveal gaps in the Standard Model, potentially reshaping our understanding of the universe. Antimatter makes up an extremely small fraction of the observable universe, so small that its percentage is functionally close to zero, less than 10^{-15}, making it practically nonexistent.[5]

But the enigma doesn't end there. Another mysterious component called dark matter makes up about 27% of the whole universe, far more than baryonic matter, which is only about 5%. In this paper, we explore the mystery of the matter-antimatter problem, while linking it to dark matter and analyzing current theories and hypotheses for the asymmetry problem and the possible connection to dark matter (DM).

This question is fundamental because without the answer, the Standard Model and General Relativity are incomplete. Recent experiments at CERN and Planck's data of the cosmic microwave background (CMB) are trying to find an answer or something that may be missing. We assert that during the matter-antimatter annihilation, the energy released may have formed, or have a possible link, to dark matter. We approach this hypothesis while examining current studies, theories, and data from previous papers, telescopes, and experiments.

This paper is organized as follows: In Section 2, we give background on matter-antimatter asymmetry, the Standard Model, CP Violation, and Dark Matter. In Section 3, we review current findings of CERN's latest experiment and Euclid's and Planck's data. In Section 4, we describe some of the existing theories that try to explain the asymmetry, including Baryogenesis, Leptogenesis, and the Higgs Field theories. In Section 5, we link the matter-antimatter asymmetry with dark matter through various theories, mainly Axion Quark Nuggets,

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Torsion Theory, and the hypothetical X particle. We end with the conclusion (Section 6), analyzing this hypothesis and possible future experiments to test it.

Discussion

Section 2: Matter/Antimatter:

To understand the asymmetry problem, it is important to first define what matter and antimatter are. In physics, matter is anything that has mass and occupies space. At the most fundamental level, matter is composed of elementary particles called quarks and leptons. Quarks, as we explained before, combine to form protons and neutrons, and together with electrons (a type of lepton), they make up atoms, such as hydrogen, oxygen, and iron, which then form molecules that create complex organic and inorganic substances and all the visible matter in the universe.

Antimatter, on the other hand, is made of anti-particles, which have the same mass as particles but opposite charges.5 In 1996, scientists at CERN managed to create the first anti-atoms, specifically antihydrogen, by combining antiprotons and positrons in a lab. They used a facility called the Low Energy Antiproton Ring (LEAR), and they confirmed that the anti-atoms were real by detecting the energy signals from their annihilation.[6] (*See Table 1 for more information on particles and anti-particles*).

Table 1: Particles and their corresponding antiparticles. They have different charges: spin number, the number that shows intrinsic angular momentum; and Baryon/Lepton Number, the number that shows what type of matter it is. Note that they have the same mass but opposite charge, Baryon/Lepton Number, but the same spin number. Antiparticles are not just theoretical; they have been experimentally observed in laboratory settings, particularly at high-energy facilities like CERN.[2,7]

Particle	Charge	Spin	Baryon/Lepton Number	Anti-Particle	Charge	Spin	Baryon/Lepton Number
Electron	-1	½	Lepton +1	**Positron**	+1	½	Lepton -1
Proton	+1	½	Baryon +1	**Anti-Proton**	-1	½	Baryon -1
Neutron	0	½	Baryon +1	**Anti-neutron**	0	½	Baryon -1
Neutrino	0	½	Lepton +1	**Antineutrino**	0	½	Lepton -1

The Standard Model states that matter and anti-matter particles form in pairs, e.g., electrons form alongside positrons, the anti-particle to electrons (Table 1) and they annihilate each other immediately according to the equation below: Standard Model states that many matter–antimatter pairs, e.g. electrons and positrons, can be produced under high-energy conditions and annihilate upon contact (Table 1). They annihilate each other immediately according to the equation below:

$$e^{-} + e^{+}\blacktriangledown \qquad \gamma + \gamma$$

where e^{-} stands for electron, e^{+} for positron, and γ for photons. So when they come in contact with each other, they release two photons, or in terms of energy, we can use Einstein's equation to find the exact value:

$$E = 2 * mc^2 = 2 * (9.11 * 10^{-31} kg)(3.00 * 10^8 m/s)^2 \approx 1022 keV$$

According to particle physics, many particles and their corresponding antiparticles were created in the early universe, shortly after the Big Bang. When these particle–antiparticle pairs met, they could annihilate each other, releasing energy, which would have left a very small amount of matter. But somehow, we have more matter than antimatter. According to theoretical models supported by cosmological observations, approximately one extra matter particle per billion survived matter-antimatter annihilation after the Big Bang to create the matter-dominated universe we observe today.[7,8] This is exactly what the matter-antimatter asymmetry problem is.

Standard Model and CP Violation:

The way that scientists choose to describe the matter - antimatter asymmetry is through the CP Violation, referring to the violation of the symmetry that was thought to be in our universe of C (charge conjugation) and P (parity). Charge conjugation transforms a particle into an antiparticle, whereas P (parity) serves as a mirror while reflecting the position of the particle that we are observing. The fact that CP symmetry is violated in our universe gives rise to the matter-antimatter asymmetry. In 1964, scientists discovered CP violation in the decays of neutral kaons,[9] and later in B-meson decays at the BaBar[10] and Belle experiments[11] in 2001 (Aubert *et al.*; Abe *et al.*). Kaons and B-mesons are subatomic particles made of quarks. In this case, one quark + one anti-quark forms mesons.[3] In the 1964 and 2001 experiments, the particles decayed differently depending on whether they were a particle or an antiparticle, while proving that matter and antimatter behave differently.

CP violation stands as a perfect solution to the big question of why we have more matter than antimatter today, but there is another problem. CP violation contributes to the asymmetry, but its effect is too small to fully explain the observed dominance of matter over antimatter. While the Standard Model of Particle Physics supports the CP Violation, for example, through neutrino oscillations,[12] the effect that CP would have on the matter-antimatter asymmetry is still so small that it does not describe the matter dominance we have today.[13] This is because at very high temperatures (like during the electroweak phase transition, happening at 10^{-12} seconds after the Big Bang, when the universe cooled enough for the electroweak force to split into two separate forces)[14] studies have shown that the CP effect is about 10 billion times too small to produce the amount of matter the universe has today.[15] This gap matters because it shows that the Standard Model alone cannot explain why matter dominates, pointing to the need for new physics and guiding future experiments to search for additional sources of matter dominance.

So, there must be another component missing that would solve the matter-antimatter asymmetry. It might be a new particle in the Standard Model or, as we suggest in this paper, a possible connection with dark matter. This is why scientists are still researching, experimenting, and theorizing.

Dark Matter:

Dark Matter is one of the most mysterious substances in our universe, whose nature is still unknown to us. It makes up about 27% (as shown in Figure 1) according to Planck's data from 2018.[16] DM (Dark Matter) can be observed only by its gravitational effects and not electromagnetic ones like we observe ordinary matter.[17, 18]

We have observed DM through:

1. Galaxy Rotation Curves - While measuring the speed of the stars' movement in galaxies, they found that the stars away from the center move faster than expected based on visible matter alone, suggesting that DM exists.[19]

2. Gravitational Lensing - Clusters of galaxies and other massive objects, bend the light due to gravity (acting like lenses) and reveal a lot about DM.[20]

3. Cosmic Microwave Background (CMB) - CMB provides information about the composition of the early universe, and missions such as Planck show that 27% of the universe is DM.[16]

4. Large-Scale Structure and Galaxy Clusters - They match simulations that include DM, proving that it plays a crucial role in universe formation.[21]

Some theories suggest that processes creating dark matter might also influence matter-antimatter asymmetry, providing a possible link between these two major cosmological mysteries.

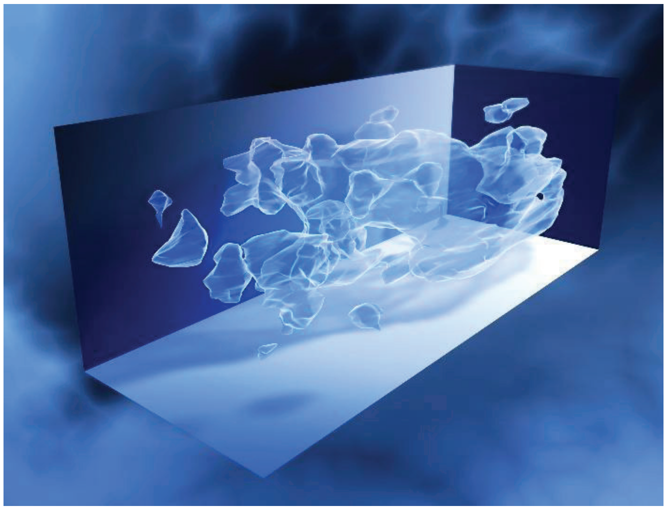

Figure 1: This figure illustrates the three-dimensional distribution of dark matter, showing that it forms complex, cloud-like structures rather than being evenly spread. These structures create a framework that influences how matter clusters and how the large-scale structure of the universe develops. (Credit: NASA, ESA).

Section 3: Current Findings:

For years, scientists have been experimenting and testing hypotheses to find a possible solution to the problem. This has been done by building huge experimental facilities like the Large Hadron Collider (LHC) at CERN and advanced telescopes such as Euclid and Planck. All these high-tech innovations have given us some incredible and physics-changing data that we describe in this section.

CERN Results:

Over the years, CERN has delivered some of the most groundbreaking discoveries (see Figure 2), including the confirmation of the Higgs boson in 2012 by the ATLAS and CMS experiments, which completed the Standard Model by explaining how particles obtain mass.[22] In March 2025, another big discovery important for the matter-antimatter asymmetry problem happened.

Scientists at the LHCb Experiment (Large Hadron Collider beauty) studied the Lambda-b (Λ^0_b), which is a baryon, consisting of a bottom (b), up (u), and down (d) quark. They also studied its antiparticle, which consists of antiquarks, and observed how these particles decay. The scientist found out that the particle and antiparticle decay in different ways. There was a measurable decay asymmetry of ~2.45%, more than 5 sigma.[23]

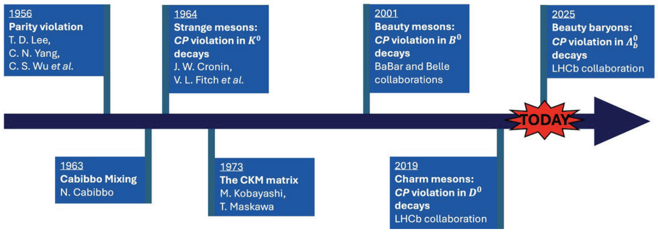

Figure 2: The figure highlights the progression and scientific significance of CERN's experiments over time. (including the latest discovery in March 2025 of LHCb for beauty baryons), Credit: CERN.

This experiment is very important because it is the first time proving that CP violation not only happens in meson decays but also in baryon decays. Even though this discovery is really crucial in understanding the asymmetry mystery, this alone cannot fully answer why matter is dominant. This is why there are other, ongoing projects and future observations being planned.

Euclid Mission:

Many projects study dark matter, and from their data, we can get crucial information that can be used towards the possible link between the matter-antimatter asymmetry and dark matter. One of these important missions is the Euclid Mission, one of the biggest telescopes that is studying dark matter. Euclid is a collaboration between NASA (National Aeronautics and Space Administration) and ESA (European Space Agency), launched on July 1, 2023. It aims to map cosmic structure via widefield optical and near-infrared imaging, covering roughly 14,000 deg^2 of the extragalactic sky. By collecting data on weak gravitational lensing and galaxy clustering, Euclid gives a very important understanding of the evolution and distribution of dark matter across half of the universe's history.[24] Studying dark matter allows great progress on the possible link between DM and the asymmetry, and Euclid is providing valuable information already. In its first data release, covering only 0.45% of its planned survey area, Euclid revealed more than 500 strong gravitational lenses, including a rare complete Einstein ring[25] and details of Abell 2390, a large galaxy cluster. An example of a recent image can be found in Figure 3. It has also cataloged over 26 million galaxies, including detailed lensing data from 380,000 galaxies, helping scientists better trace how dark matter is distributed.[26]

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Figure 3: The Einstein Ring produced by gravitational lensing around galaxy NGC 6505. Light from a more distant galaxy is bent into a ring by the foreground galaxy's gravity, illustrating a key prediction of general relativity (Credit: Euclid).

The Planck Space Telescope:

Besides large particle colliders and missions like Euclid, scientists also study the early universe and the matter–antimatter asymmetry using data from space-based telescopes like ESA's Planck Space Telescope. According to the Planck 2018 results,[16] the universe consists of approximately 26.8% dark matter and only 4.9% ordinary (baryonic) matter.

The main goal of Planck is to study the CMB and the evolution of the early universe, which can be very useful for dark matter, asymmetry, and early universe models that scientists are currently studying. Planck has already given some really important details about our universe, which are really helpful to understand the asymmetry from the CMB anisotropies, to very small variations in temperature and density that reflect and confirm the matter-antimatter asymmetry. Moreover, its data have also been used in some proposed models and mechanism explain the asymmetry. In the upcoming sections, we are going to explain these models in a detailed way, including data that support or contradict them.

Section 4: Views on the matter-antimatter asymmetry:

The matter-antimatter asymmetry in the observable universe is usually studied within the concept of baryogenesis,[27] a process that explains an extra generation of baryons (matter) over antibaryons in the early universe. For baryogenesis to occur, certain conditions, known as the Sakharov conditions,[28] must be satisfied: baryon number violation, meaning that early-universe reactions created more matter than antimatter; C and CP violation, meaning that particles and their corresponding antiparticles behave differently; and departure from thermal equilibrium, meaning that the universe was not in equilibrium due to its rapid expansion.[4, 29, 30]

One promising theory within baryogenesis is Leptogenesis (subsection 3.1), which describes the matter-antimatter imbalance while focusing on the lepton asymmetry.

Leptogenesis:

We have already stated our hypothesis about connecting the matter-antimatter asymmetry to dark matter, but the imbalance mystery is an old, unsolved problem that has sparked hundreds of ideas and hypotheses about the origin of this problem. We already talked about the CP violation as a possible explanation for the problem, but since it cannot fully explain all the dominant matter, there must be other explanations. For example, one possible explanation that scientists have suggested is Leptogenesis.[31] In the Standard Model of particle physics, there are certain quantities called Baryon number (B) and Lepton Number (L), which are usually conserved.

Leptogenesis proposes that conservation of L can sometimes be violated, allowing right-handed neutrinos to decay and produce more leptons than antileptons. These lepton asymmetries can then be converted into the baryon asymmetry that we observe today. This can be a possible explanation of why there is more matter than antimatter in the universe today.[32] However, even though Leptogenesis can explain why the asymmetry exists, it has some limitations because it depends on the existence of right-handed neutrinos and specific CP-violating interactions, both of which have not yet been experimentally confirmed. Dark matter could play a complementary role in addressing these limitations, either as an independent component or as being produced alongside the lepton asymmetry.

Higgs Field and Asymmetry:

Leptogenesis is one of the most studied theories that tries to explain the asymmetry, but there are also other theories. One of them involves the Higgs field, a fundamental part of the Standard Model that gives particles their mass.[33] Scientists have suggested that after inflation in the early universe, the Higgs field oscillated in a way that violated CP symmetry, creating an imbalance between matter and antimatter similar to what we observe today. For example,[33] shows that the oscillations of the Higgs field after the inflation could have caused a lepton asymmetry of about $|nL / s| \approx 2.4 \times 10^{-10}$, a value present both in Planck data and theoretical models,[33, 34] which is very close to the observed matter dominance. However, this mechanism alone cannot fully explain the matter-antimatter asymmetry, because it involves very specific conditions in the early universe, and additional components (such as dark matter) may play a role in explaining the observed asymmetry.

Section 5: How is the asymmetry linked to dark matter?:

Section 3 already gave us insight into the different theories that scientists have come up with to explain the asymmetry. In this section, we describe the connection between matter-antimatter asymmetry and DM through existing theories. However, we want to point out that it is very hard to verify them. It would require a lot of time, infrastructure, and modern equipment to prove these theories because it is very hard to de-

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tect "invisible" particles, but if we do so, it will change physics as we know it.

Axion Quark Nugget (AQN) model:

The Axion Quark Nugget (AQN) model offers a potential unified explanation for both matter–antimatter asymmetry and dark matter formation. According to this theory,[35] the universe started with equal amounts of matter and antimatter, but it does not describe the antimatter as being annihilated.

It proposes that the antimatter transformed into extremely dense objects called "antiquark nuggets." These nuggets do not interact with visible light or regular matter; they are "invisible," like how dark matter behaves. At the same time, axions (very light, neutral, weakly interacting, and potential dark matter particles proposed in the 1970s to solve the CP problem)[36] are part of the model that hides antimatter in dense objects and helps support the quark nuggets (illustrated in Figure 4).

This theory is notable because it suggests that antimatter is not annihilated, but rather transformed into a hidden form.[37] However, the model relies on hypothetical particles (axions) and assumptions about quark nugget formation, and these are not yet confirmed experimentally. If this theory is correct, it would explain how the asymmetry is connected to DM, but more importantly, would solve two of the biggest mysteries in the field of cosmology: why matter won over antimatter, and what dark matter is. A strength of this model is that it links dark matter and asymmetry with a single mechanism, though its predictions are very difficult to test. Experimental tests, such as axion detection experiments or searches for quark nugget interactions, could help support or falsify this model.

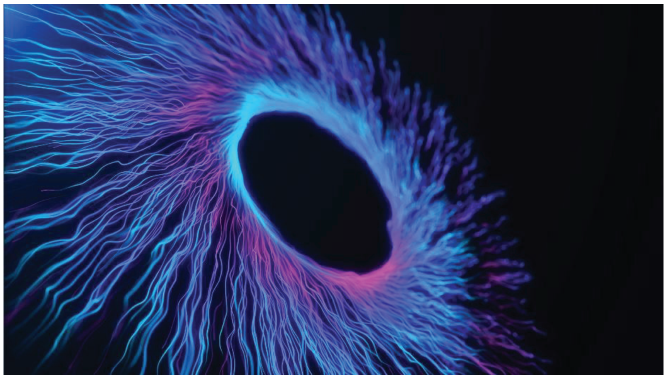

Figure 4: Conceptual illustration of axions, the target of ongoing experimental searches for dark matter (Credit: Quanta Magazine).

Subsection 5.2: Torsion Theory:

There is another theory that scientists have hypothesized to explain dark matter formation, and that it can lead to a link to the asymmetry problem. This theory uses a new branch of Einstein's Theory of Relativity. Relativity states that spacetime curves in accordance with mass and energy, which is what gravity is. But according to the theory, spacetime not only curves, but it can also twist. This twisting is what is called torsion, and it is thought to interact with particles that have intrinsic spin, such as electrons or quarks, rather than implying literal physical spinning. This theory provides a different approach from models like Axion Quark Nuggets, as it modifies spacetime itself rather than introducing new particles. Scientists research whether they can include torsion in current cosmological models, for example, in the Friedmann equations, which explain how the universe expands, and to see if there is a gravitational effect similar to that attributed to dark matter. This would be a very new and interesting approach to dark matter. They suggest that this torsion behaves like the effects of dark matter, so there are ways to describe DM without needing new particles to describe dark matter. However, these ideas remain theoretical, and future observational tests are needed to determine if torsion can indeed explain dark matter and the asymmetry problem. If torsion can explain dark matter, it could also play a role in the asymmetry problem.[38, 39] Some recent theories have speculated that torsion fields could induce CP violation or baryon/lepton number-violating processes (described in the previous section) in the early universe, by contributing this way to matter dominance. Its advantage is explaining dark matter without new particles, but the mechanism is still not experimentally confirmed. However, these ideas are still not proven experimentally and need further testing. Future observational tests may help determine if the torsion theory would be the one to solve the two biggest mysteries with just one answer.[40]

Subsection 5.3: X particle:

There is a new particle proposed that does not fit in the Standard Model called the "X" particle.[41] This particle is unique because it behaves differently from every known particle and can represent a new form of matter or maybe something that we are missing. To start with its uniqueness, the X particle decays into ordinary matter (like neutrinos), whereas the anti-X decays into "dark matter particles." This can explain matter dominance quite easily. Its mass is expected to be around 1000 GeV[41] (about a thousand times the mass of a proton), quite heavy compared to the few GeV other DM proposed particles. According to scientists, the X particle does not have to interact like the other SM particles. They actually suggest that its interactions are in a "hidden sector" with dark decay channels.[41] This particle could fill the gap between the asymmetry problem and the Standard Model. Since SM cannot fully explain the asymmetry, maybe this mysterious particle can explain it and make up most of the universe's mass, but still be invisible to us, characteristics that correspond to DM. To verify this hypothesis, scientists are still working with large experiments like CERN's LHC and investigating the properties of the X particle. The X particle model could directly show new physics, but it heavily relies on discovering a particle that has not yet been observed. If confirmed, the X particle can actually change cosmology and particle physics by solving two of the biggest mysteries and showing that DM and asymmetry correlate with each other.

This model is different from Axion Quark Nuggets and Torsion theory because it introduces a new particle instead of modifying spacetime or using dense objects. Scientists can test this idea by looking for the particle at CERN's LHC. Comparing these tests with predictions from other models can show which of these theories explains both dark matter and the matter-antimatter imbalance best.

Conclusion

In this paper, we looked at the possible link between dark matter and the matter-antimatter asymmetry by exploring different theories that try to explain the asymmetry, starting with CP Violation in the Standard Model. We also went over the CERN, Euclid, and Planck 2018 results. Before discussing theories that connect dark matter with the asymmetry, we introduced Baryogenesis, Leptogenesis, and the Higgs Field theory, which try to explain the asymmetry without involving dark matter. Finally, we explored beyond Standard Model ideas, including Axion Quark Nuggets, Torsion, and the X particle.

Each model has its own strengths and weaknesses. The Axion Quark Nugget model links dark matter and asymmetry with a single mechanism, though it's hard to test. Torsion Theory can explain dark matter without new particles, but it's still theoretical. The X particle could reveal completely new physics, but it depends on finding a particle that hasn't been observed yet.

All of these theories need experimental proof, but future projects give hope. The Nancy Grace Roman Space Telescope, with its advanced gravitational lensing and stellar analysis, will map dark matter in the universe. The Vera C. Rubin Observatory will perform a 10-year survey, giving detailed data about both the early and current universe. Together, these studies might help figure out which models, or combination of models, best explain the matter-antimatter asymmetry and dark matter.

In short, there's still a big gap between theory and experiment, but upcoming projects like the Roman Space Telescope and the Vera C. Rubin Observatory could lead to discoveries that change our understanding of cosmology, astrophysics, and particle physics in the next few decades.

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I attest that the ideas, graphics, and writing in this paper are entirely my own. All figures, data, and sources used in this review have been properly cited and credited.

Thank you!

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