Searching for Dark Matter: WIMPs, Axions and Others

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Abstract: It's widely accepted that dark matter makes up nearly 27% of the universe, yet its actual nature is still unknown. Contemporarily, scholars have devised several ideas to explain this mysterious form of matter. Two of the most talked-about candidates are WIMPs (Weakly Interacting Massive Particles) and axions, but others like sterile neutrinos and even tiny black holes have also been suggested. This research will go through these possibilities, focusing mainly on how researchers try to detect them. For WIMPs, one looks at direct detection efforts deep underground, indirect searches using signals from space, and tests done in colliders such as the LHC. For axions, one explains their theoretical background and how experiments like ADMX and CAST use strong magnets and sensitive equipment to find them. This study also compares the latest results and points out what areas scientists have already ruled out. While no confirmed signals have shown up so far, newer tools and better methods are helping narrow things down. Understanding dark matter matters not just for physics but also for figuring out how the universe came to be and how it behaves today.

1 INTRODUCTION

Even though one can see stars, galaxies, and gas clouds in space, scientists say all of that only makes up about 5% of the universe. A much larger part, i.e., roughly 27%, is something one can't see at all: dark matter. The idea of dark matter came up nearly a hundred years ago when astronomers noticed that galaxies were moving in ways that didn't match what one expected based on visible matter. In 1933, Fritz Zwicky studied galaxy clusters and realized they were moving too fast to be held together just by what one could see (Zwicky, 1933). Later in the 1970s, Vera Rubin found something similar while looking at how stars move around in galaxies. Their speed didn't slow down at the edges like it should have, which again hinted at some invisible mass (Rubin, et al., 1 980).

This mysterious substance, i.e., dark matte, isn't just interesting for astronomers. It's super important because it helps explain how galaxies formed in the first place and how the universe looks today. The most widely used model for understanding the universe, called the ΛCDM model, actually depends on dark matter to explain why galaxies and clusters formed the way they did (Planck Collaboration, 2018). Scientists think if one figures out what dark matter really is, it could help answer some of the biggest questions in physics and even open the door to new discoveries beyond what one knows now (Bertone & Hooper, 2018).

While one knows dark matter is there because of how it affects gravity, it is still unknown what it's made of. That's why scientists have come up with different ways to try to find it. Some are looking for tiny particles called WIMPs (Weakly Interacting Massive Particles), which are believed to rarely hit normal atoms. There are giant underground experiments like XENON1T and LUX-ZEPLIN that are trying to catch these hits (Aprile et al., 2018; LZ Collaboration, 2022). So far, they haven't found anything for sure, but they've managed to rule out certain kinds of WIMPs, which helps focus the search.

Others are studying axions, which are super light particles that were originally suggested to fix a problem in particle physics. Axions might be turning into tiny bits of light (photons) when passing through a magnetic field, and experiments like ADMX and CAST are trying to catch that signal (Du, et al., 2018; Anastassopoulos, et al., 2017).

Some scientists are also looking into other ideas, like sterile neutrinos, particles that barely interact with anything, or even mini black holes that might have formed in the early universe (Carr, et al., 2020). Tools like the Fermi Gamma-ray Telescope and the

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Large Hadron Collider (LHC) are also being used to see if they can find any indirect signs of dark matter (Aaboud, et al., 2017; Fermi-LAT Collaboration, 2015).

Even though no one has directly found dark matter yet, the search has become more exciting because one now has better technology and more ideas. The goal of this paper is to take a closer look at the three most talked-about types of dark matter candidates: WIMPs, axions, and some of the more unusual options like sterile neutrinos and tiny black holes. Each type comes from different theories in physics and requires different tools to detect.

The paper is organized into several parts. First, this study will explain what dark matter is and the main types that scientists think it might be. Then, this study will go into more detail about WIMPs, including what they are, how trying to detect them, and what results gotten so far. After that, this study will do the same for axions, talking about where they come from and how scientists are searching for them. The next section will focus on other possible dark matter candidates that don't get as much attention but are still important. Finally, this study will compare all of these options, what is still unknown, and what future research might look like. By going over these different ideas and experiments, this paper aims to give a clear picture of where dark matter research stands today and where it might go next.

2 DESCRIPTIONS

Most of what one sees in the universe, e.g., stars, planets, and galaxies, only makes up a small part of what's out there. Scientists think that around 27% of the universe is made of something called dark matter. As shown in Fig. 1, the pie chart represents the percentage of matter in the universe. Dark matter cannot be observed for now, and it does not give off light or energy, but one knows it is there because it affects the things one sees. For example, galaxies spin faster than they should base on the matter one can detect. That tells scientists that something else must be adding extra gravity (Bergström, 2012). Dark matter can be split into two main groups: baryonic and non-baryonic. Baryonic dark matter is made of regular stuff like too-faint stars or black holes that don't shine. However, the problem is that there is just not enough of this kind of matter to explain what one sees in space. That is why scientists believe most dark matter is non-baryonic, completely different from the normal matter one knows (Feng, 2010).

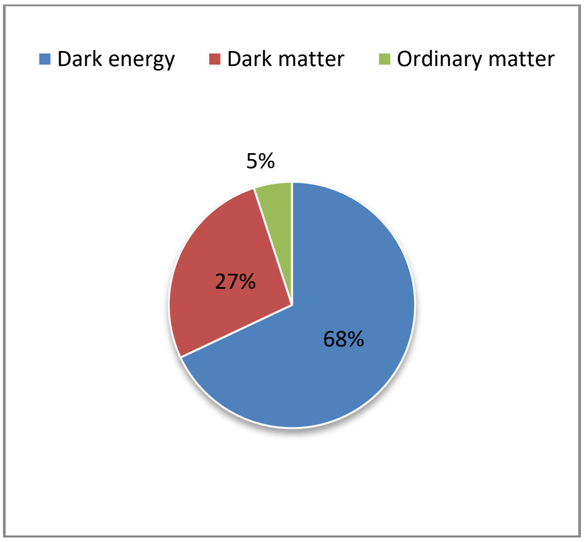

Figure 1: Proportion of matter (Photo/Picture credit: Original).

Non-baryonic dark matter is also sorted into types based on how fast its particles were moving in the early universe:

- Cold dark matter (CDM) is made of slow-moving particles. They stick together and help form galaxies. WIMPs, or Weakly Interacting Massive Particles, are one of the top candidates for CDM (Roszkowski et al., 2017).
- Warm dark matter (WDM) particles are a bit faster and might explain some things that CDM can't.
- Hot dark matter (HDM) moves really fast (e.g., neutrinos), but this type doesn't help form structures very well.

So far, WIMPs are the most widely studied. These particles would barely interact with normal matter, which is why one hasn't seen them directly. Scientists use big labs like the Large Hadron Collider (LHC) to try to create or spot them, but no proof has been found yet (Roszkowski, et al., 2017). Another interesting idea is the axion. This particle is super light and comes from theories trying to fix problems in particle physics. Axions might have been created early in the universe, and scientists are now testing if they can turn into light under certain conditions (Feng, 2010). There's also a theory about sterile neutrinos. They'd be even harder to detect than regular neutrinos, but some experiments are trying to find signs of them by looking at how they might decay (Bergström, 2012). In short, even though dark matter is still invisible to us, one has good reasons to think it's real. And with better tools and ideas, scientists are slowly narrowing down what it could be.

3 WIMPs

One of the most talked-about ideas for what dark matter might be is something called WIMPs, or Weakly Interacting Massive Particles. These are particles that are thought to have mass and only interact through gravity and the weak nuclear force, which is why one can't see or feel them. Even though WIMPs haven't been discovered yet, they're still one of the most popular dark matter candidates in modern physics (Roszkowski, et al., 2018).

Because WIMPs don't give off or reflect light, scientists must look for them using indirect methods. There are three main ways to do this: direct detection, indirect detection, and particle collider experiments. Direct detection is all about trying to "catch" a WIMP as it passes through Earth. Scientists build underground labs with detectors filled with liquid xenon or argon. These detectors are placed deep underground to block out background noise from cosmic rays. One of the newest and most advanced experiments is XENONnT, located in Italy. In 2023, the team announced the results of their first run. They didn't find WIMPs yet, but they set some of the strictest limits on what kind of WIMPs might still be out there (Aprile, et al., 2023).

Another major direct detection experiment is LUX-ZEPLIN (LZ), which is located in South Dakota, USA. Like XENONnT, it uses liquid xenon to detect tiny flashes of light caused by potential WIMP collisions. The liquid xenon detector is filled with very pure liquid xenon, and if a WIMPs hits a xenon atom, it might cause a tiny flash of light or release a small electric signals. And scientists use these signals to figure out if a dark matter particle might have passed through. Their first results, published in 2022, didn't detect any WIMPs either, but just like XENONnT, the experiment helped rule out many earlier models that are now considered unlikely (LZ Collaboration, 2022).

The second method, indirect detection, doesn't look for WIMPs themselves but for the signals they might leave behind. If two WIMPs smash into each other, they could produce gamma rays or neutrinos. Telescopes and detectors like Fermi or IceCube are used to look for these kinds of signals. So far, none of the signals have been strong or clear enough to confirm the existence of WIMPs.

The third approach involves collider experiments, especially at the Large Hadron Collider (LHC) in Switzerland. This massive machine smashes particles together at high speeds. If WIMPs are created in these collisions, scientists might see signs like "missing energy" in the data. But even though LHC results from 2022 showed some unusual patterns, none of them were strong enough to confirm a WIMP discovery (ATLAS Collaboration, 2022).

Even though all three methods haven't found WIMPs yet, scientists aren't giving up. In fact, each experiment helps narrow down what WIMPs could be, i.e., if they exist at all. These results help design better detectors and improve future experiments. Plus, the search for WIMPs is helping scientists better understand the universe, even if the particles stay hidden for now.

4 AXIONS

Axions are one of the lesser-known, but really important, dark matter candidates. They weren't originally invented to explain dark matter. Instead, they were proposed as a solution to a weird puzzle in particle physics called the strong CP problem. Basically, this is something that should make particles behave in an unbalanced way—but in real experiments, they don't. So, scientists came up with a new particle, the axion, to fix that. Later, they realized axions also had the right properties to explain dark matter. Because axions are tiny, stable, and don't interact much with regular matter, they could be floating around in the universe without us noticing them (Sikivie, 2021).

What makes axions different from other dark matter particles like WIMPs is that they're very light. But even if they're tiny, they could exist in huge numbers; enough to make up a large part of the universe. The problem is that they're so weakly interacting that one needs special tools to have a chance of detecting them.

There are two main ways scientists are trying to detect axions: haloscope and helioscope experiments. Haloscope experiments look for axions in the galaxy that might be passing through the Earth all the time. These experiments rely on the fact that axions are predicted to sometimes turn into photons (particles of light) when they pass through a strong magnetic field. That's where detectors like ADMX come in. ADMX stands for Axion Dark Matter eXperiment. It uses a strong magnet and a special chamber called a microwave cavity to look for tiny signals—like an axion changing into a photon that gives off a bit of energy (Bartram, et al., 2021).

Axion detectors are built around the idea that these particles might very rarely turn into light when they pass through strong magnetic fields. That's why many experiments use powerful magnets as their main component. In halo scope setups like ADMX, a very strong magnet is placed around a microwave cavity—a specially designed metal chamber that resonates at certain frequencies. If an axion turns into a photon inside the cavity, it will create a tiny amount of energy that the system can pick up. The trick is that the signal is extremely small, so the whole setup must be kept super cold and shielded from noise to catch even the slightest effect. On the other hand, helioscope experiments like CAST and the upcoming IAXO aim their magnets toward the Sun, hoping to catch axions that might be flying out from it. If one of those axions turns into a photon in the magnet, a sensor can detect the light. These tools need to be extremely precise, since the expected signals are weaker than anything dealing with in everyday life. That's why scientists keep building better magnets and more sensitive detectors. Even though one hasn't seen axions yet, every test brings us closer to either finding them or ruling out where they might be hiding.

The ADMX team made a big leap in 2021 by searching a new range of axion masses. This range is one of the most likely regions where axions are predicted to be. They didn't detect anything yet, but they showed that the detector is sensitive enough to find axions if they're out there.

The other approach is called a helioscope. Instead of looking for axions coming from space in general, these detectors look at the Sun. Some theories say that axions could be created in the Sun's core and fly out into space. When they pass through a magnet here on Earth, they could turn into photons. The CERN Axion Solar Telescope (CAST) did this for years. Now, a newer, more powerful version called IAXO (the International Axion Observatory) is being built. It will have stronger magnets and better detectors, which should make it possible to search a wider range of axion masses (Irastorza & Redondo, 2022).

Other experiments like HAYSTAC and QUAX are also trying different ways to find axions. Some are using quantum sensors to boost their sensitivity. Even though no one has found axions yet, more and more of the possible axion "mass space" is being tested. In physics, ruling things out is just as important as making discoveries. The fact that axions might solve not just one, but two big mysteries—dark matter and the strong CP problem—makes them worth all the effort. Axion research might not be as famous as WIMPs or black holes, but it's one of the most promising areas in the search for dark matter. With better tools and more experiments on the way, scientists hope that one might be getting closer to the answer.

5 OTHER CANDIDATES

Even though WIMPs and axions usually get most of the attention when people talk about dark matter, they aren't the only ideas out there. Some scientists are also looking into different kinds of particles or objects, like neutrinos and primordial black holes (PBHs). These aren't new theories, but they're still being taken seriously and are part of the bigger search to figure out what dark matter really is.

Neutrinos are super tiny particles that hardly interact with anything at all. They're flying through everything (Earth, the bodies, even solid rock) basically all the time, and one barely notices them. Since they have a little bit of mass, they were once thought to be a good candidate for dark matter. But the thing is, they move fast. That makes them bad at "clumping together," which is something dark matter has to do to help galaxies form. Because of that, most scientists think neutrinos can't be the main part of dark matter. Still, some newer ideas suggest that in certain conditions, like if they form something called condensates, neutrinos might act more like slower-moving cold dark matter and maybe be part of the bigger picture (Buettner & Morley, 2022).

Then there are primordial black holes, which are way different from the black holes one hears about in space documentaries. These didn't come from exploding stars. Instead, they might have been created right after the Big Bang, when parts of the universe were so dense that they could've collapsed into black holes. They could come in all sorts of sizes—from teeny ones to one's way bigger than the Sun. Since they only mess with things through gravity, they could totally act like dark matter. Some scientists, (e.g., Carr & Kühnel, 2020), think it's still possible that PBHs could make up dark matter, especially in a few mass ranges that haven't been ruled out yet.

Neutrinos are usually studied using huge underground labs. One example is IceCube in Antarctica. It's basically a giant sensor frozen into the ice that looks for tiny light flashes when a neutrino hits something. It's a cool setup and has helped us learn a lot, but it hasn't proven that neutrinos are the dark matter looking for. PBHs are trickier. The smallest ones should've already disappeared through a process called Hawking radiation. But the bigger ones might still be around. Scientists try to find them by looking at how their gravity bends light from faraway stars. This is called microlensing. Another way is by looking for gravitational waves—ripples in space made when black holes crash into each other. LIGO has found some of these collisions, and a few scientists wonder if the black holes involved could've been primordial.

Thus, neutrinos and PBHs aren't the most popular theories right now, but they haven't been ruled out either. And looking into all these different ideas helps scientists keep an open mind. In the end, even if they're not the final answer, they're helping us get closer to figuring out what's really going on in the universe.

6 COMPARISON, LIMITATIONS AND PROSPECTS

After learning about all the different dark matter candidates, it's clear that each one has its strengths and weaknesses. WIMPs, axions, neutrinos, and primordial black holes all try to explain the same mystery, but they come from totally different ideas in physics.

WIMPs are still one of the most popular candidates because they fit nicely with theories like supersymmetry. They're also supposed to have the right kind of mass and speed to match how dark matter should behave. The problem is that after decades of searching, one still hasn't found one. Experiments like LUX-ZEPLIN and XENONnT are super sensitive now, but they keep coming up empty. Thus, while WIMPs still make sense on paper, it's hard to stay confident without real evidence.

Axions are different. They were invented for something else, solving the strong CP problem in particle physics, but ended up being a possible dark matter solution too. What makes them cool is that they're super light and barely interact with anything. Experiments like ADMX are finally reaching the sensitivity needed to look for them, and there's a lot of excitement about what future detectors like IAXO might find. However, again, no solid results yet.

Then, there are the "other" candidates. Neutrinos are interesting because one knows they exist, and they have mass. Nevertheless, they move too fast to explain how galaxies formed the way they did. Still, people are thinking of ways they might act differently under certain conditions. Primordial black holes are probably the weirdest idea, they come from the early universe and wouldn't interact with anything except gravity. There's no need to invent new particles, but it's also hard to prove they're even there. The big limitation in all of this is the fact that scholars haven't found anything directly. Most of the work so far is based on ruling things out rather than finding what works. That's frustrating, but it's also part of science. Human beings are asking questions no one has ever answered before, and the tools one needs are just now becoming good enough.

One big reason to be optimistic is that detection technology is improving fast. Scientists are finding ways to reduce background noise, cool detectors to even lower temperatures, and use more stable magnets. At the same time, new methods like quantum sensing are helping increase sensitivity to the tiniest signals. Another key improvement is in energy resolution, the ability to tell apart very small differences in energy. By designing better microwave cavities and using more precise amplifiers, experiments can now scan a narrower range of frequencies more carefully. That means they're less likely to miss something just because it was slightly outside the expected range. Bit by bit, these upgrades make it more likely that one will finally catch a signal that's been hiding in the noise all along.

7 CONCLUSIONS

To sum up, the search for dark matter remains one of the most important questions in modern physics. This study examined several leading candidates: WIMPs, axions, neutrinos, and primordial black holes. Each of them offers a possible explanation, but none have been confirmed. WIMPs were long considered the most likely, but no direct evidence has been found. Axion experiments are becoming more sensitive and show promise. Neutrinos are well understood but likely too light and fast. Primordial black holes present an alternative approach but are difficult to detect. Although no candidate has been verified, ongoing experiments continue to narrow the possibilities and improve the understanding. Every test, even those that rule something out, brings us closer to the truth.

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