How can we hunt for dark matter?

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1 Introduction

In 1904, renowned scientist Lord Kelvin published a book, titled “Baltimore Lectures on Molecular Dynamics and the Wave Theory of Light”, built on several lectures he had given in 1884. In this, he proposed that, if there were a billion stars near the Sun, the majority of them would have to be “dark bodies”. This is regarded as one of the first references to dark matter.

Dark matter has been a major focus in the astrophysics community for decades. It is a form of matter that does not interact with the electromagnetic force, making it virtually undetectable by our telescopes. However, we know it exists due to gravitational phenomena, which suggest that there must be more mass in the universe than we can observe. One of the biggest unsolved mysteries in physics is the nature of dark matter, and although several theories have been put forward to explain what dark matter is made up of, there has been little concrete evidence to support these ideas. To solve this issue, methods of detecting different types of dark matter have been developed, to varying degrees of success.

In this review, we will discuss the evidence we have for the existence of dark matter. We will then explore potential candidates for dark matter, and assess these to find the most plausible theory. We will break down different methods of detecting dark matter, then justify which is the best method. Finally, we will conclude by evaluating the extent to which methods of hunting for dark matter have been successful, and whether we will be able to detect dark matter in the future.

2 Evidence for dark matter

Fundamentally, celestial bodies behave as they do because of gravity. Our current best model of gravity is Einstein's theory of general relativity, however, in many cases it is simpler to approximate this theory using Newton's law of gravitation and Kepler's laws of planetary motion. However, these approximations could not account for observations made of galaxies and other bodies, which showed a large discrepancy between theoretical and experimental results. This seemed to imply that there was a flaw in our understanding of the Universe, leading to the proposition of dark matter to explain these observations.

2.1 Galaxy velocities and the virial theorem

The first evidence of dark matter came in the form of velocities of galaxies in clusters. By measuring the velocities of galaxies in a cluster, we can determine a mean velocity of the galaxies. This enables us to obtain a relationship between mean velocity and the mass of the cluster.

Galaxies in a cluster obey the virial theorem, which states that, for a system affected by a (conservative) force:

$$\langle T\rangle = -\frac{1}{2}\langle U\rangle \tag{1}$$

Here, T represents the kinetic energy, U represents the potential energy and the angled brackets denote an average (mean). In the case of a cluster of galaxies, these quantities become:

$$\langle T\rangle = \frac{1}{2}M\langle v^2\rangle \tag{2}$$

where M = mass of the cluster, R = radius of the cluster and:

$$\langle U\rangle = -\frac{3}{5}\frac{GM^2}{R} \tag{3}$$

(the gravitational potential is assumed to be that of a sphere of uniform density).

Substituting these quantities into the virial theorem:

$$\frac{1}{2}M\langle v^2\rangle = \frac{3}{10}\frac{GM^2}{R} \tag{4}$$

Solving for $\langle v^2\rangle$ we find:

$$\langle v^2\rangle = \frac{3GM}{5R} \tag{5}$$

In 1933, physicist Fritz Zwicky used the above procedure to predict the velocities of galaxies in the Coma Cluster. He estimated that $\mathrm{R} \approx 1$ million light years, roughly 10^{22} m, and used a currently accepted value of $\mathrm{M} \approx 1.6 \times 10^{42}$ kg (based on visible luminous matter). Using this and (5) he calculated:

$$\langle v^2 \rangle \approx (80 \text{ km s}^{-1})^2 \tag{6}$$

Next, Zwicky experimentally determined the velocities of galaxies in the cluster. He did this by measuring the frequencies of electromagnetic (EM) waves emitted by gases in stars within the galaxies, when electrons move to lower energy levels in atoms. It is possible for us to precisely measure the frequency of these waves on earth, however, the frequencies of EM waves that we detect from the galaxies is different to these. This is because of the Doppler effect: the apparent shift in the frequency of waves being emitted by a moving wave source. By comparing the frequency of waves arriving from the galaxies to the expected frequency of the waves, we can determine the shift in frequency and using this deduce the velocity of the galaxies. By measuring the Doppler shifts of galaxies in the cluster, Zwicky concluded that:

$$\langle v^2 \rangle \approx (1000 \text{ km s}^{-1})^2 \tag{7}$$

Although Zwicky's value was an overestimate, he correctly found that galaxies in the Coma Cluster were moving much faster than could be explained by luminous matter. As suggested by equation (5), to explain this much larger velocity, there must be a much larger mass contained within the galaxy than could be observed – 400 times greater according to Zwicky's calculations. Zwicky proposed that there was a large quantity of unseen mass which held the galaxies in the cluster together, even at high velocities – which he dubbed "dark matter".

2.2 Galaxy rotation curves

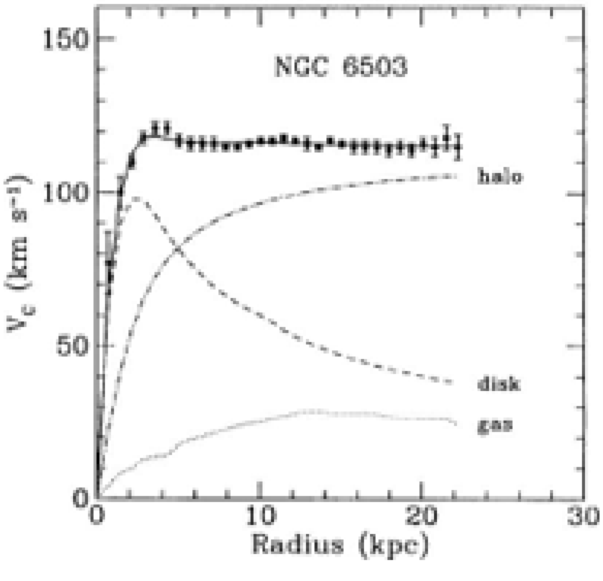
Early evidence of dark matter also came from studying galaxy rotation curves. This is a graph of the speeds at which stars orbit the centre of a galaxy - where most of the luminous (visible) mass of the galaxy is located - against their distance from the centre of the galaxy (orbital radius). Orbital speed is dependent on the mass of the galaxy. If we assume that luminous matter is spherically distributed throughout the galaxy, then we can use circular motion equations to describe the dynamics of stars:

$$G\frac{Mm}{r^2} = \frac{mv^2}{r} \tag{8}$$

$$v = \sqrt{\frac{GM}{r}} \tag{9}$$

This shows that if the mass of the galaxy increases, then orbital velocity will be higher and as orbital radius increases, velocity should decrease. Galaxies tend to have a more complicated mass distribution, however, more sophisticated models taking this into account predict a similar relationship.

By finding the orbital velocities of stars using their Doppler shifts, we can plot a galaxy rotation curve. For a typical spiral galaxy (NGC 6503 below), the rotation curve is:



Orbital velocity initially increases from 0 to around 3kpc. This is because the luminous mass in the centre of the galaxy is not concentrated at a singular point; instead, it is distributed over a small region. Then as radius increases, the mass enclosed within this radius increases by a greater factor than radius, leading to an overall increase in orbital velocity.

More interesting, however, is the behaviour of orbital velocity beyond a 3kpc radius. From 3kpc onwards, orbital velocity remains roughly constant even as orbital radius increases. This is in direct contrast to equation (8), which suggests that $v \propto \sqrt{\frac{1}{r}}$ and would therefore decrease with radius.

In order for velocity to remain constant, mass of the galaxy would need to increase with radius. Specifically, this implies that

$$M(r) = kr \tag{10}$$

where M is the mass enclosed within a given radius r, and k is a constant.

Substituting this into equation (8):

$$v = \sqrt{\frac{Gkr}{r}} \tag{11}$$

$$v = \sqrt{Gk} \tag{12}$$

meaning that v is constant with radius (G and k are constants).

In order for (10) and hence (12) to hold, there must be a large amount of mass in galaxies beyond its centre. However, from our observations of galaxies using EM waves, there does not appear to be much luminous mass in this region. This implies that there is some kind of mass here which does not interact with EM waves – this is dark matter.

2.3 Gravitational lensing

Gravitational lensing is a phenomenon predicted by general relativity, in which a mass can bend the path of light as it travels from a source to an observer. This occurs because the presence of the mass distorts the shape of the space around it (as proposed by general relativity). This curved space has curved geodesics through it – this is the shortest path between two points in space. Because light travels along the path that takes the least time to traverse (Fermat's principle), it must travel along this geodesic. This causes light to appear to an observer as if it is curving around the mass. The larger the mass, the greater the distortion of space and the stronger the lensing effect. There are several types of gravitational lensing, one of which is strong lensing – this is gravitational lensing by a large mass, which can lead to the formation of arcs. We can measure the extent to which bodies behind a cluster (which acts as a lens) are distorted into an arc, allowing us to quantify the effect of lensing. Knowing this, we can determine the mass of the cluster.

Once the mass of the cluster has been determined, we need to find the luminosity of the cluster. The luminosity of a star is the quantity of energy it emits per unit time. Only visible matter has a nonzero luminosity (as it gives off energy in the form of light). Finding luminosity involves measuring the apparent brightness of the cluster at a point, and estimating the distance of the cluster from this point. Once luminosity has been determined, we can calculate a mass-to-light (M/L) ratio – this is simply a ratio of the mass of the cluster to its luminosity. It is usually written as a multiple of a constant $M_\odot/L_\odot$ (the mass-to-light ratio of the Sun, which is made up entirely of visible mass).

Using gravitational lensing, M/L ratios of clusters have been obtained, and these tend to be larger than $M_\odot/L_\odot$. For example, a study of 105 nearby galaxy clusters yielded an average value of 250 $M_\odot/L_\odot$ for their M/L ratio. This indicates that not all of the clusters' mass is in the form of luminous matter. Instead, there must be dark matter in these clusters contributing to their mass, much larger in quantity than the luminous mass.

Strong gravitational lensing can also lead to multiple images of an object being formed. This can occur when light from galaxies behind a cluster travels along different geodesics around the lensing cluster to an observer. Each geodesic corresponds to a different apparent position of the galaxies to the observer, leading to multiple images. By measuring the positions of these images, it is possible for us to determine the geodesic that light travelled along, and from this we can infer how mass is distributed in the cluster. If there is no visible mass in regions which we believe to have mass, then we can infer that dark matter must lie here. This has provided evidence that dark matter is distributed in certain regions in clusters.

2.4 CMB radiation

Cosmic microwave background (CMB) radiation provides evidence for the Big Bang model of the universe, but it also implies the existence of dark matter.

CMB is a remnant of the early universe, which was a plasma of tightly interacting photons and matter particles (mainly protons and electrons) following the Big Bang. As the Universe expanded and cooled, these protons and electrons began to form hydrogen atoms. This prevented photons from interacting with them, in a process called decoupling, and as a result these photons were released, travelling through the Universe as high-energy gamma rays. However, as the universe expanded over time, the wavelength of these waves increased, resulting in the microwave radiation that we detect today, coming from everywhere in space.

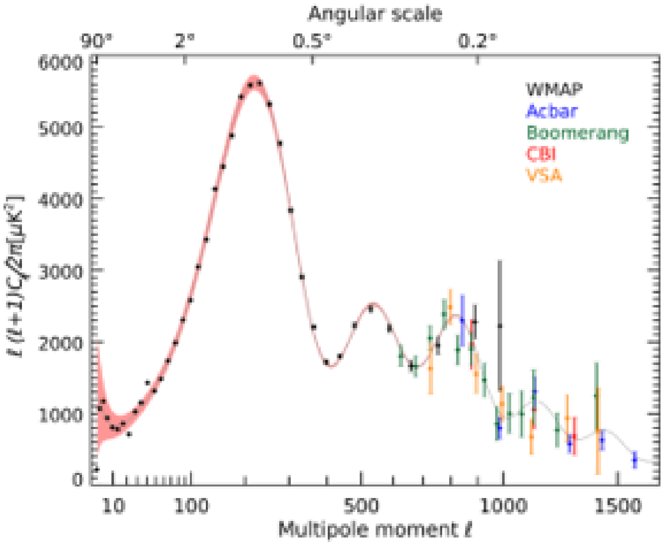
Although the CMB is remarkably uniform in all directions, we have detected tiny temperature fluctuations in the CMB – these are known as anisotropies. There are different causes of these anisotropies.

Because there is relative motion between the CMB radiation and observers on Earth, the wavelength of the CMB radiation is shifted as a result of the Doppler effect, which causes the measured temperature to change (temperature of a wave is inversely proportional to its wavelength). The CMB that is moving in the direction of the Earth's motion appear to have a decreased wavelength, and therefore appears hotter. This is known as the dipole anisotropy, and is the largest anisotropy in the CMB.

There are also much smaller anisotropies, due to interactions of matter with radiation in the early universe. During this period, ordinary (baryonic) matter was charged and was therefore able to interact with EM radiation, leading to temperature fluctuations that we observe today.

Dark matter, provided that it exists, would have a different impact on CMB radiation. This is because dark matter cannot directly interact with EM radiation. However, it can affect CMB radiation via the force of gravity. For example, if a large enough amount of dark matter was concentrated in a region of the early universe, it could create a gravitational potential well. As EM radiation leaves this well, it loses energy, causing its wavelength to increase – this is known as gravitational redshift – and its temperature to decrease, leading to anisotropies that we observe today. Because dark matter interacts differently with CMB radiation to baryonic matter, it will lead to different anisotropies that can be separated.

The anisotropies in the CMB that we measure today have an associated frequency, related to their distribution in the sky. This enables us to plot a graph known as a power spectrum:



The above power spectrum has three characteristic peaks, from which we can deduce different properties of the universe. The first peak tells us that the universe is spatially flat. The second peak reveals the quantity of baryonic matter in the universe.

The existence of a third peak implies that there is another factor apart from baryonic matter causing anisotropies in the CMB – suggesting that dark matter does indeed exist. This third peak quantifies the density of dark matter in the universe. By measuring the shapes of the three peaks, alongside higher order peaks, we have been able to conclude that while ordinary matter makes up 5% of the mass-energy content of the universe, dark matter makes up 26.8% of this. This means that there is much more dark matter than ordinary matter in the universe.

3 Dark matter candidates

Since the proposition that dark matter does indeed exist, several contenders have emerged regarding its identity. However, the theories associated with these candidates have their own advantages and limitations, and there is no definitive evidence favouring a single candidate over all the others. This has made it very difficult to discern which candidate is most likely to make up dark matter. To be considered as viable options, dark matter candidates should satisfy several criteria:

- They should not emit or interact with electromagnetic radiation.
- They must be stable on cosmological timescales or have a long enough lifetime to still be present today.
- For cold dark matter (the most widely accepted type of dark matter), candidates should have velocities much less than the speed of light.

In this section, we will evaluate which candidates are most probably the building blocks of dark matter.

3.1 Weakly Interacting Massive Particles

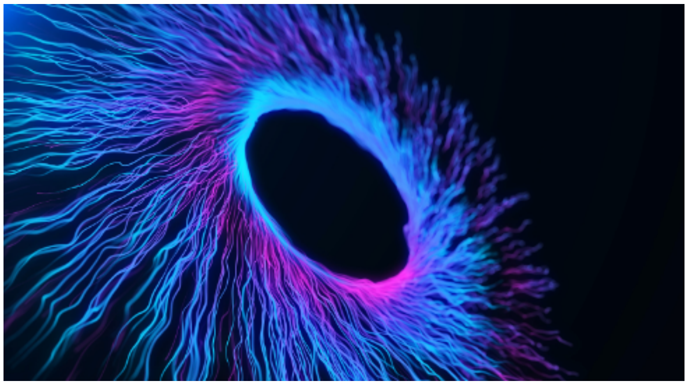
Weakly Interacting Massive Particles (WIMPs) are currently the most popular dark matter candidate, due to their consistency with many physical theories and similarities to the hypothesised nature of dark matter.
A WIMP is an elementary particle which can interact via gravity, and any other hypothetical forces which are weaker than the weak force. As suggested by the their name, WIMPs are thought to have a high mass - in the range of 100 GeV/c^2, which is significantly heavier than most particles in the Standard Model of particle physics. WIMPs are believed to have been produced thermally in the early universe, similar to other particles in the Standard Model. The probability that enough WIMPs (to account for the amount of dark matter we observe today) were produced thermally seems to fall in line with their expected mass.

One of the reasons that WIMPs are good candidates for dark matter is their tendency to interact only with very weak forces. This means that they do not interact with the weak force, which would explain why dark matter is so difficult to detect. Moreover, because WIMPs have a high mass - and therefore low velocity - this would match the consensus that the majority of dark matter in the universe is cold dark matter (dark matter which moves at very low speeds). Cold dark matter would form large clumps, as their low velocity is insufficient to overcome their mutual gravitational attraction, which agrees with current observations of the shapes and sizes of galaxies. Furthermore, many supersymmetric models of the universe predict the existence of dark matter particles with similar properties and evolution with time to WIMPs, which could indicate that they indeed exist.

However, the theory of WIMPs has some flaws. For example, particle colliders, such as the Large Hadron Collider at CERN, have not yet observed the expected signatures of WIMPs and related supersymmetric particles, creating doubt about their existence. Another drawback of WIMPs is that, even if they exist, the search for such particles is limited by their few and weak interactions, meaning that very specific and powerful tools would be required to observe them. Hence more research is required before we would be able to definitively say that dark matter is made of WIMPs.

3.2 Axions

Another main candidate for dark matter are axions. These are a type of hypothetical elementary particle which were originally proposed to solve the strong CP problem in Quantum Chromodynamics (QCD), and, if they exist, could be a possible component for dark matter. However, unlike WIMPs, the masses of axions range, and can be very low, on the scale of $10^{-5} - 1\ eV/c^2$, but despite this, they can have a relatively low velocity. Oscillations of the field associated with axions generate a population of low-velocity axions, with abundances depending on their mass. It turns out that axions with a mass much less than 60 keV/c^2 are long-lived and weakly interacting, making them the perfect candidates for dark matter. Axions with a mass above $5\mu eV/c^2$ could account for dark matter, making them both a dark matter candidate and a solution to the strong CP problem. Unlike WIMPs, axions are believed to interact with all four fundamental forces, but very weakly. However, this raises issues as to why none have been detected thus far, possibly making them a slightly weaker candidate than WIMPs.

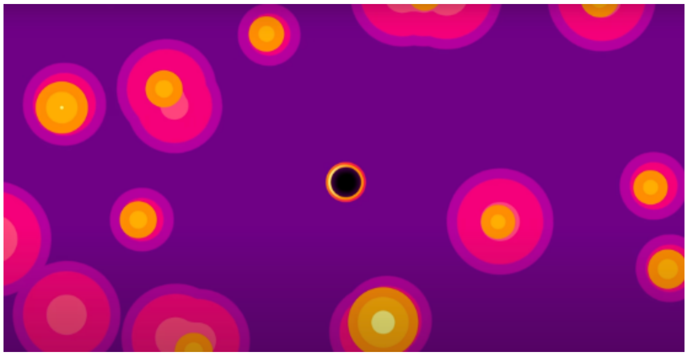


The strong CP problem is a fundamental issue in QCD. In the Standard Model of particle physics, QCD allows for charge-parity violation, which would lead to observable effects such as a non-zero electric dipole moment for the neutron. However, no significant CP violation has been observed in strong interactions. To solve this issue, the Peccei-Quinn theory was proposed. According to this theory, a new field called the axion field helps to cancel out the unwanted effects of CP violation. While this theory has resolved the strong CP problem, it has also predicted the existence of axions. This theory gives the axion unique properties, including having a very light mass and extremely weak interactions with other particles. These predictions align with the properties of dark matter and therefore provide a strong theoretical basis for considering axions as a dark matter candidate. As axions can have low velocities, they are able to clump together and hence are a possible candidate for cold dark matter.

Axions also come with their own limitations. Axions interact very weakly with ordinary matter and electromagnetic fields. They are hypothesised to interact primarily via a coupling with photons. This would allow axions to convert into photons in the presence of a strong magnetic field; however, the signal produced by this interaction is expected to be very small. This means that experiments need to be extremely sensitive and well-shielded from background noise to have any chance of detecting axions. Furthermore, the wide range of possible axion masses makes experimental searches more complicated, as searches across a larger range of masses need to be undertaken. The production and abundance of axions in the early universe presents another challenge. The predicted abundance of axions is highly sensitive to the inflationary conditions of the early universe. If these factors are not precisely understood, the predicted axion density might not match the observed dark matter density. This inconsistency would mean that axions are unlikely to be the primary component of dark matter.

3.3 Primordial Black Holes

Primordial black holes are a cold dark matter candidate that are significantly different from other candidates, as they are not particles. Instead, they are incredibly small black holes which were created in the first second after the Big Bang. They formed from extremely small pockets of hot material, which were just dense enough to collapse under their own gravitational pull to form black holes. In the early universe, matter was very compressed due to the small size of the universe at that time, resulting in many pockets of high density, leading to a high number of primordial black holes forming. The masses of such black holes are thought to range from between 100,000 times lower than that of a paperclip, to 100,000 times heavier than the Sun. Although the black holes with a low mass would have evaporated by now (due to the effects of Hawking radiation), the ones with large masses would remain, meaning that they are still present in the current universe (provided they exist). However, due to the high density of black holes, even primordial black holes with the mass of the Earth would be no larger than a coin, making them small and difficult to detect, especially at a large distance.



Dark matter candidates can be classified into baryonic and non-baryonic (a baryon is simply a type of composite subatomic particle which contains an odd number of valence quarks, such as protons and neutrons), with primordial black holes falling under the non-baryonic category (along with all other candidates on this list), since they are not "made up of" quarks, which makes them more likely to be a viable explanation for dark matter. However, regular black holes, which are baryonic (since they are created from collapsed stars), are also considered as potential candidates for dark matter - falling under a category of similar candidates like brown dwarfs, called Massive Compact Halo Objects (MACHOs) - due to the fact that smaller, stellar mass black holes quite difficult to observe as well, and so could also explain some of the dark matter in the universe. Although primordial black holes are much more likely candidates for dark matter, it is still important that ordinary black holes are considered as well.

The extremely high mass of such objects would be beneficial when explaining the existence of dark matter, given that it makes up such a large proportion of the matter in the universe, meaning that primordial black holes have been at the forefront for a possible explanation for dark matter since their proposal. Also, gravitational wave detectors such as the LIGO detector are undergoing research which makes the existence of such black holes increasingly likely, meaning that they are becoming even more favoured as a dark matter candidate, since black holes have very strong gravitational attractions, which is one of the key features of dark matter. Their very stable nature, and extremely rare chance of colliding with other objects, further reinforce their standing as potential dark matter candidates, as it would make sense that none have been detected so far. Unlike WIMPs, primordial black holes are able to emit gravitational waves which interact with regular matter, which would more directly explain the effect of dark matter on the rotational velocity of stars at the edges of galaxies. These black holes are also able to account for certain effects of gravitational lensing which cannot arise from regular matter, further highlighting the likelihood that they have at least some contribution to the effects of dark matter which we can currently observe, provided that they exist.

Despite their many strengths, primordial black holes also have drawbacks when it comes to their applicability to being a dark matter candidate. One of the biggest of these drawbacks is that tight limits have been placed on the abundance of these black holes in the universe, as a result of various cosmological and astrophysical observations, meaning that they would not contribute significantly to the amount of dark matter we see in the universe over most of their plausible mass ranges, and so would be insufficient to account for dark matter alone. Also, the extremely large distances between objects in space mean that, even if there were primordial black holes currently in the Solar System, detecting them with their incredibly small size would be close to impossible, so other methods might need to be considered, like with WIMPs. Finally, primordial black holes require very specific conditions to have formed in the early universe, such as large density fluctuations, whereas the current Cosmic Microwave Background

(CMB) hints at a more evenly distribution of mass in the early universe than might necessarily be required for the existence of these black holes, meaning that, even if they exist, they would be very few in number.

3.4 Sterile neutrinos

Sterile neutrinos are another candidate for dark matter. Unlike the three types of (active) neutrino in the Standard Model (electron, muon and tau neutrinos) that interact via the weak nuclear force, sterile neutrinos do not interact through any of the Standard Model forces except for gravity. They are hypothesised to have a mass ranging from a few keV/c^2 to several GeV/c^2. This mass range is higher than that of active neutrinos but is generally lower than other dark matter candidates such as WIMPs. They are predicted to have a very long lifetime, often exceeding the current age of the universe. Sterile neutrinos could have been produced in the early universe through a variety of mechanisms, such as thermal production or through the decay of heavier particles. They can be produced thermally through interactions involving active neutrinos or other particles in the hot, dense conditions shortly after the Big Bang. This process is similar to how standard neutrinos are produced.

Sterile neutrinos, especially those in the keV mass range, are likely to have high velocities so are a good candidate for warm dark matter. Warm dark matter has a higher velocity than cold dark matter, which means that it is more spread out and less likely to collapse under gravity into very small structures. This aligns well with the observed number of dwarf galaxies around larger galaxies. Warm dark matter also predicts that dark matter haloes (discs of dark matter that surround galaxies) have a lower central density compared to cold dark matter models - this prediction appears to be consistent with observations of the density profiles of galactic haloes. As sterile neutrinos have a long lifetime, they are suitable as a dark matter candidate as their weak interactions mean they would not decay quickly.

One key limitation of the theory of sterile neutrinos is that they are predicted to decay, although very slowly, into lighter particles, such as active neutrinos or photons. This decay would produce a characteristic X-ray signal, however, no evidence of these X-ray lines have been found, leaving their existence uncertain. These signals would need to be observed more consistently to suggest that sterile neutrinos are a major component of dark matter. Furthermore, if sterile neutrinos are too light, their velocities would be too high, which would lead to few small-scale structures forming - this would be inconsistent with observations. However, the exact mass range for which this becomes a problem is still debated.

3.5 Kaluza-Klein Particles

The final key dark matter candidate to discuss are Kaluza-Klein particles. These are particles of the Standard Model - which usually travel at a certain known speed - but appear to be travelling at a slower speed than their expected one, causing them to appear to have a higher mass than they actually do. The reason for this lower speed and higher mass is due to the particles travelling through extra spatial dimensions on a microscopic scale. As they are travelling through extra dimensions, the particles have to cover a larger distance in the same period of time, and so have a lower speed. An analogy to this would be an ant on a straw. To a far away observer, it appears as though the ant can only move up and down the straw, but in reality the ant can also move around the circumference of the straw, causing it to move a greater distance in the same period of time than if it only moved up or down the straw. It is only possible to see the curvature of the straw by getting closer to it, similar to these extremely small dimensions.

Other than the higher mass of Kaluza-Klein particles, they are believed to share most of the same properties of the original versions of their particles, and so should be relatively simple to detect under the correct conditions, as physicists know what to look for. The reason why Kaluza-Klein particles are a potential dark matter candidate is due to the properties of the lighter particles of this family which make them suitable to be dark matter. For example, these particles interact mainly through the weak force, and some of them can have very long lifetimes due to the conservation laws associated with extra dimensions, such as Kaluza-Klein parity. These weak interactions make them very difficult to detect, which is consistent with the elusive nature of dark matter and the range of masses which some of these particles can exist in also correspond with the expected mass for a cold dark matter particle, making them suitable candidates.

One of the major advantages which this dark matter candidate has over the others is that it can hypothetically be directly observed here on Earth with our current technology. The LHC at CERN currently has two detectors, the Compact Muon Solenoid (CMS) and A Toroidal LHC Apparatus (ATLAS), which are seeking to observe particles with a mass heavier than they should have, in hopes of proving the existence of Kaluza-Klein particles. Doing so would be a major breakthrough which would also massively further research in the field of dark matter, as any theories currently made could be experimentally tested, unlike with other candidates. Another advantage of Kaluza-Klein particles is that their existence is predicted by many other theories, such as supersymmetric theories, string theory and higher-dimensional theories. They also arise as a natural consequence of Kaluza-Klein theory, which aimed to unify gravity and electromagnetism by introducing a fifth dimension. This demonstrates their expected nature, and shows that Kaluza-Klein particles are likely to exist, more so than some of the other dark matter candidates, making their existence both likely and verifiable experimentally.

However, Kaluza-Klein particles, like the other candidates, have some disadvantages. Despite many theories predicting their existence, these models are typically very theoretically complex, requiring different manifolds of spatial dimensions and new particles to exist in order to function correctly, whereas most of the other candidates are much simpler in nature and so may be more likely to exist. Also, the theories themselves are still incomplete, and so it is unreliable to rely on them alone to confirm the existence of such particles, when none have been observed experimentally to date. Additionally, even though the LHC at CERN may be able to detect Kaluza-Klein particles, the collider sensitivity to these particles can diminish if there are small mass splittings between the Kaluza-Klein particles and others on the spectrum. For example, when the Kaluza-Klein quarks become lighter than the Kaluza-Klein photon, the collider signatures can become less pronounced, which means it may also be difficult to detect Kaluza-Klein particles.

3.6 Summary of section

Overall, it is clear that each of the candidates for dark matter could possibly be an explanation for its identity, as they each have properties that make them suitable for this. The most likely outcome is therefore that the dark matter present in our current universe is in fact a combination of these candidates, with some, more likely candidates making up a larger proportion of this dark matter. Although our current technology may be too limited to immediately detect any of these particles or objects, it is definitely not unfeasible to observe them, and in the near future Physicists should have the necessary apparatus to conduct experiments to confirm the existence of one or more of these dark matter candidates, allowing us to reach a definitive conclusion about the true composition of dark matter. Despite not being the easiest to detect, WIMPs and axions are definitely among the main candidates because of the variety of required properties of dark matter which they demonstrate. However, the other candidates still remain important possible explanations which cannot be instantly rejected and must still be considered in the search for what makes up dark matter.

4 Methods of detecting dark matter

Due to its non-luminous nature, it is very difficult to detect dark matter and as a result we have had to use different methods to gain information about its behaviour. There are three main ways of detecting dark matter: direct detection, indirect detection and creation.

4.1 Direct detection

Direct detection involves attempting to directly measure dark matter in collisions with atoms, assuming that dark matter exists as WIMPs. The leading detector for direct detection is the LUX-ZEPLIN (LZ). LZ is the successor to the ZEPLIN-III detector, which was built specifically for dark matter research. The LZ is considered to be a major improvement from the ZEPLIN-III for many reasons; the most important being improved sensitivity, which is vital in dark matter detection. Another important program for detecting dark matter is the CDMS II (Cryogenic Dark Matter Search II), a set of multiple experiments conducted under specific, extreme conditions. The most recent experiment was the SuperCDMS which took readings until late 2015.

One of the major features of any dark matter detector is that they are built underground. This is done to reduce the impact of background radiation that constantly reaches the surface of the Earth. By building the detector underground, it is protected from the “noise” that could block the dark matter signals. However, even underground, the people and the apparatus used are a major source of background radiation. This remains a challenge that needs to be addressed.

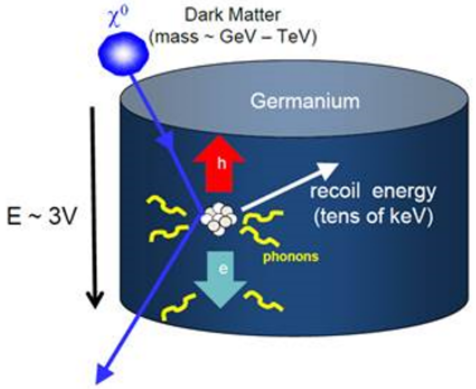
4.1.1 The Cryogenic Dark Matter Search II

The CDMS II (Cryogenic Dark Matter Search II) experiment is situated at the Soudan Underground Laboratory, Minnesota, 714m below the surface. As mentioned, the experiment focuses on detecting WIMPs. There are several components to the detector, including shielding systems, cold hardware and transition-edge sensors. The detectors are kept at temperatures very close to absolute zero, approximately 50 mK, to minimise thermal noise – this allows us to detect very small signals and energies deposited by collisions.

4.1.2

Stages of operation

1. The first stage involves the interaction of a WIMP with an atomic nucleus. When a WIMP passes through the detector material (silicon or germanium), the kinetic energy of the WIMP is transferred to a nucleus in the material, which causes the nucleus to recoil.
2. The second stage involves the detection of WIMPs:
   - When the nucleus recoils, it transfers some of its energy to neighbouring atoms, which cause them to vibrate, resulting in the production of phonons (these can be thought of as quanta of vibrations), and also causes the atoms to become ionised.



- These phonon waves propagate through the detector material and are detected by the transition-edge sensors:
  - The CDMS ZIP detector has four sensor quadrants in the top face. Each quadrant has 1040 tungsten transition-edge sensors, with each sensor attached to a 350μm long aluminium collector known as an aluminium fin. When aluminium is cooled below 1.2K (its critical temperature), it demonstrates a property known as superconductivity - no electrical resistance.

  - When the phonons are generated from a collision between a WIMP and a nucleus, the phonon waves propagate through the germanium or silicon lattice structure.

  - Phonons with a certain amount of energy (specifically, twice that of the superconducting gap energy in aluminium) can break the Cooper pairs present in the aluminium fins – these refer to a loosely bound pair of electrons in a superconductor.

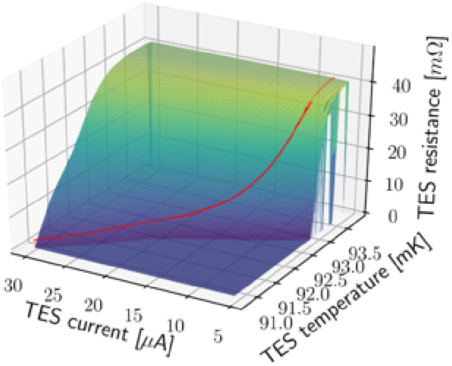
  - The breaking of a Cooper pair creates quasiparticles (in this case, the quanta of energy in a crystal lattice). These quasiparticles diffuse through the aluminium fins towards the tungsten transition-edge sensors.

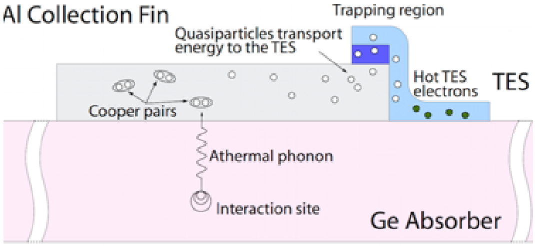
  - The minimum energy required for a quasiparticle is lower in tungsten than in aluminium, so when the quasiparticles enter the transition-edge sensors, they quickly lose energy by emitting low-energy phonons. These phonons cannot re-enter the aluminium, so are trapped in the transition-edge sensor.

  - The tungsten transition-edge sensors also demonstrate superconductivity. They are operated just below their critical temperature of 80mK, so it is in the superconducting state and shows zero resistance.

  - The release of low-energy phonons results in a small increase in temperature, causing the temperature of the transition-edge sensor to exceed the critical temperature. The sensor no longer behaves as a superconductor, and has a nonzero resistance. This transition from the superconducting state to the normal state results in a large, measurable increase in resistance.

  - This change in resistance is directly proportional to the amount of energy deposited by the particle.





- As the recoiling nucleus collides with nearby atoms, it also ionises them, which results in the formation of electron-hole pairs:
    - In the silicon/germanium lattice, electrons exist in two energy levels: the valence band (lower energy level) and the conduction band (higher energy level). The electrons released during ionisation are excited to the conduction band. These electrons have a high momentum, allowing them to excite other electrons to the conduction band. When the electrons move to the conduction band, they create regions with an absence of negative charge (electrons) in the valence band - these are known as electron holes and are effectively a positive charge.

    - Electrodes are used to apply an electric field across the detector, attracting electrons towards the anode and holes towards the cathode (if there was no electric field, then the electrons and holes would diffuse through the lattice and recombine).

    - As the electrons and holes collect at the electrodes, they induce a change in current, which is proportional to the number of charge carriers that are collected. This current change produces a signal.

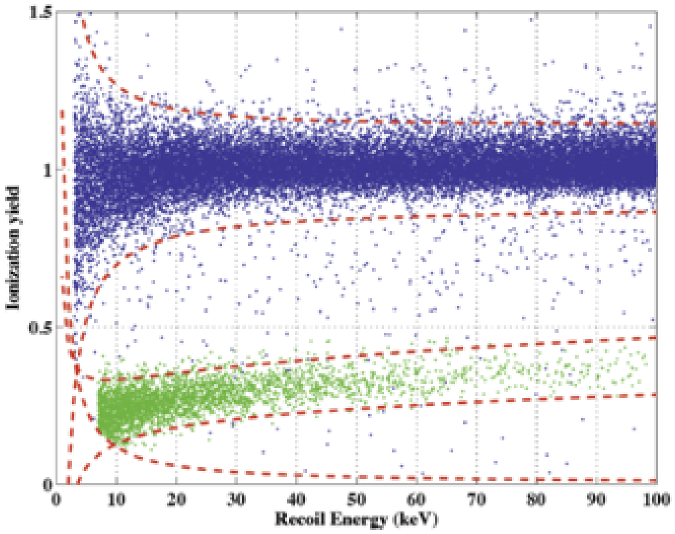
    - Capacitors at the inner electrode of the detector are used to transfer the signal from the electrode to an amplifier, which boosts the small signal to allow it to be more easily measured.

    - The collection of charge carriers at the cathode an anode results in a rapid change in the voltage across the electrodes, which means that the signal typically has a sharp rise followed by an exponentially decaying tail.

    - The amplified signal is read out as an analog signal, where the height of the pulse is directly proportional to the total charge collected, which is related to the energy deposited by the particle interaction.

3. The third stage involves signal discrimination:

   - The total energy deposited by a particle interaction is shared between ionisation and the generation of phonons.
   - Signal discrimination involves analysing the ratio of phonon to ionisation energy signals.
   - Typically for a detector, this ratio depends on the particle type and energy, as different types of particles (e.g. WIMPs, neutrons, cosmic/gamma rays) would interact differently with the detector material.
   - The phonon to ionisation ratio can help to distinguish between nuclear recoils due to WIMPs and electronic recoils due to gamma rays or X-rays. This is because electron recoils have a much higher ionisation yield (high phonon-to-ionisation ratio) because a larger proportion of the energy goes into ionising atoms, whereas nuclear recoils have a suppressed ionisation yield as more energy is channelled into phonon generation.



The graph shows a clear separation between the electron recoils and nuclear recoils, which allows for the rejection of electron recoil events.

4.1.3 Why are silicon and germanium used?

There are several reasons why silicon and germanium are used in the CDMS:

- Both materials can be produced with a very high purity – by minimising the amount of impurities in the material, we can maximise their chances of detecting fainter, weaker signals, potentially produced by WIMPs. This is because the impurities can act as regions where electrons and holes can recombine, which could make the ionisation signal detected too weak to measure.

- Both silicon and germanium have a consistent lattice structure with a regular, repeating arrangement of atoms. This allows phonons to be efficiently transmitted through the structure, and ensures that the transition-edge sensors can accurately detect low-energy interactions. Imperfections or disruptions to the lattice arrangement can lead to scattering of phonons. This causes the oscillation effects of the phonons to diminish, reducing the sensitivity of the sensors, as small energy deposits produced from dark matter candidates would go undetected.

- Both elements are semiconductors, so they are ideal for producing electron-hole pairs, which contribute to the ionisation signals.

- Silicon and germanium can maintain their regular lattice structure and electronic properties at cryogenic temperatures, where the thermal vibrations of atoms are minimised.

4.1.4 Neutron background

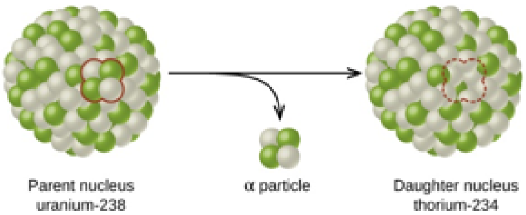
The most challenging backgrounds to discriminate from are nuclear recoils from neutrons, as the interaction between neutrons and nuclei result in similar energy depositions and so produce similar signals to those expected from WIMP interactions. There are 2 main sources of neutron background:

1. Cosmic ray induced neutrons

   High energy muons produced by cosmic rays in the atmosphere can penetrate deep underground. These muons can release neutrons through processes such as spallation (when a nucleus is bombarded by high-energy particles). Even though there is a significant amount of shielding in place, some high-energy muons can still reach the detector and produce neutrons.

2. Radiogenic neutrons

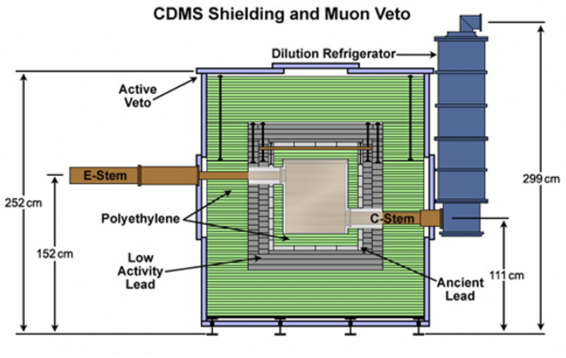
   Neutrons are also directly produced from the decay of uranium and thorium, which are present in the materials surrounding the detector:



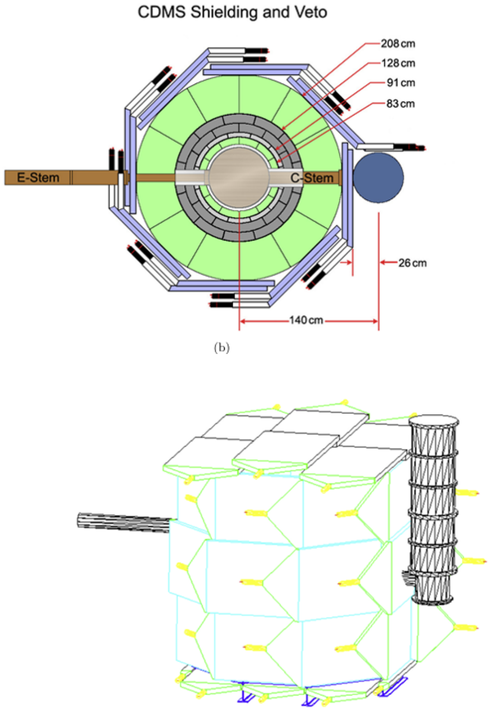
However, the rate of radiogenic neutron events are so low that they can be considered to be negligible.

4.1.5 Mitigating the effect of neutron background

1. Underground laboratory and shielding methods
    - The detectors are placed approximately 700m underground, reducing the number of cosmic ray muons reaching the detector.
    - The detectors consist of a 40cm thick polyethylene outer layer, two lead layers, as well as a mu-metal shield to block external magnetic fields.
2. Muon veto systems
    - The muon veto system consists of about 40 plastic scintillator panels that are arranged around the entire detector to detect muons passing through. Photons released by muons (in a process known as scintillation) are detected by photomultiplier tubes, connected via acrylic light guides.
    - If a muon is detected, then any associated event in the detector is flagged and removed from the WIMP search data.
    - The muon veto system has an efficiency of about 99.9225%, meaning that most neutron interactions are correctly identified and rejected.



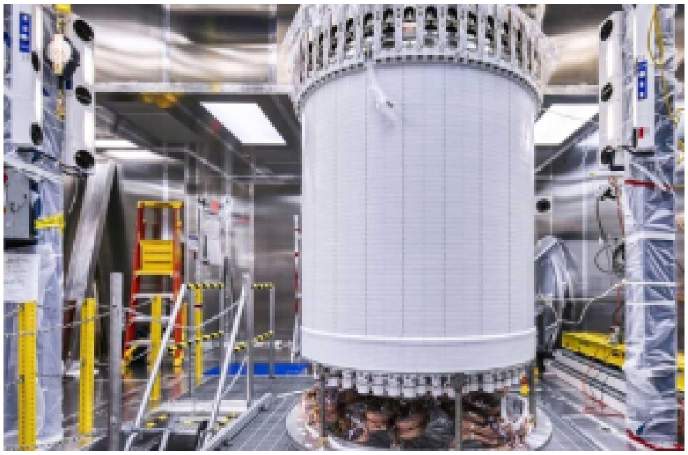
(a)



Above: The various mitigation strategies used.

4.1.6 The LUX-ZEPLIN detector

The LZ is located in the Sanford Underground Research Facility, South Dakota and is regarded as the leading detector in dark matter research.



The LUX-ZEPLIN (large underground xenon) detector uses xenon to detect dark matter. Liquid xenon is contained in the middle of the apparatus, surrounded by photodetectors. If a WIMP collides with the xenon, characteristic flashes of light would be produced, which would be detected by the photodetectors.

4.1.7 Why is xenon used?

Despite the fact that xenon is radioactive so could affect the detection of WIMPs, it is used in the LZ as it has several advantages:

- Naturally, xenon is a relatively radiopure element, which makes the entire process of screening and selecting samples simpler.
- Xenon has a high relative atomic mass, meaning each atom contains a large number of protons and neutrons, which WIMPs can interact with.
- Xenon scintillates (emits light when excited), enabling photodetectors to be used to detect dark matter.
- Xenon is transparent to the light it emits during scintillation, so it does not affect the light reaching the photodetectors.
- Xenon has many stable isotopes, meaning that a combination of isotopes can be used in the detector. This means that a larger range of dark matter events can occur, which increases the chance of an event. This is necessary since events are thought to be extremely rare.

4.1.8 Background radiation

Similar to the CDMS, background radiation is a factor that can limit the effectiveness of the LZ, however, rather than just neutron background, there are several types of background radiation that can affect the LZ:

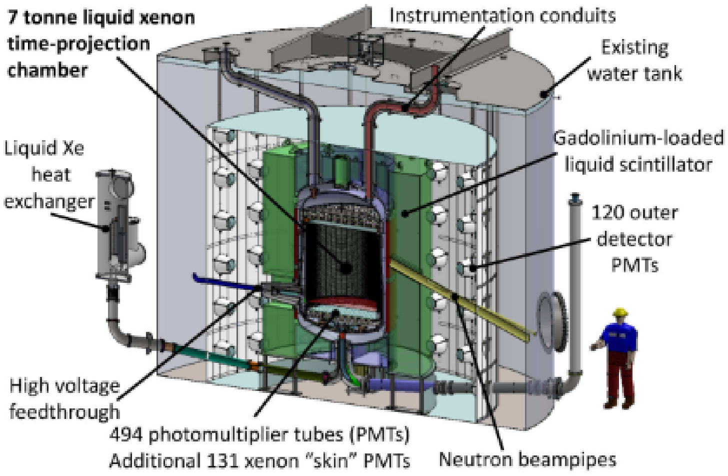
- Cosmic rays constantly bombard the Earth's surface and if the detector were to be placed here, there would be a large amount of noise, making it difficult to successfully detect any events.
- The people working around and the apparatus used in the detector are all small radioactive sources. This can build up over time, potentially affecting the experiment.
- The xenon used in this experiment is also a radioactive source. With the large quantity used (around 7 tonnes), this may also lead to a large build up of radiation.
- The xenon could also contain contaminants that may be detrimental for the experiment.
- Radon can escape from other detector components and contaminate the xenon in a process called emanation (the escape of radon atoms into pores). This accounts for around 66% of the projected background radiation.

- Radioactive dust on surfaces is another issue, especially as it is not practical to cleanse all apparatus and people. However, several policies were introduced to minimise its effect.

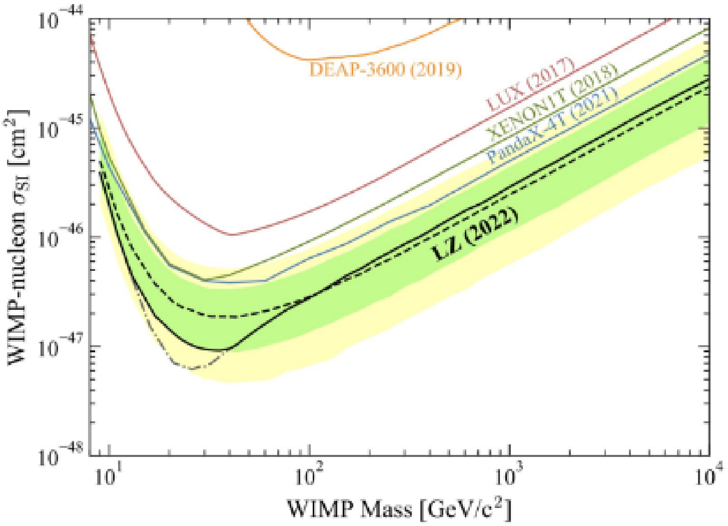
Mitigating the effect of background radiation

- The LZ is situated 1 mile underground to minimise interference from cosmic rays. This reduces noise, so that quieter signals (potentially from WIMPs) can be detected.
- The xenon used has to be as pure as possible. This includes selecting the most radio-pure samples and then removing contaminants from the xenon (which can take up to a year).
- The detector contains a xenon skin that prevents particles such as protons and neutrons from entering the detector, which could potentially contaminate the source.
- The process of radon emanation was carefully analysed. It was realised that this cannot be fully mitigated, so the amount of radon gas that underwent the emanation process was measured, which can be linked to any events that occur.
- All personnel working directly with the functioning of the detector were made to wear full body protective equipment in order to reduce carriage of radioactive dust.
- The tank is made from medical grade titanium, which itself sits in a larger tank filled with water as a shield.

However, even this level of sensitivity seems to be insufficient for detecting dark matter at the LZ, as no conclusive data was collected. This suggests that the LUX-ZEPLIN's measures must be improved upon to proceed in the hunt for dark matter.


7 tonne liquid xenon time-projection chamber
Instrumentation conduits
Existing water tank
Gadolinium-loaded liquid scintillator
Liquid Xe heat exchanger
120 outer detector PMTs
High voltage feedthrough
494 photomultiplier tubes (PMTs)
Additional 131 xenon "skin" PMTs
Neutron beampipes

In 2017, the LZ took its first readings, which did not collect any different data to others. However, in 2022, the LZ collected data which established the lowest bound on the mass of WIMPs (provided they exist) to date.



4.2 Indirect detection of dark matter

The Large Hadron Collider at CERN is designed to collide protons at very high energies, and one of its goals is to search for dark matter candidates.

In order to do so, missing transverse energy (MET) needs to be measured. This refers to the imbalance of energy and momentum in the plane perpendicular to the direction of the proton beams used in the LHC. In particle collisions, the total energy and momentum before and after a collision must be conserved. Before a collision, the protons are fired along the z-axis, which means that the momentum in perpendicular planes before the collision must be zero. After the collision, the total momentum in these planes should still sum to zero. However, if the measured transverse momentum is non-zero, this suggests that some particles have been undetected, which may be dark matter candidates.

Events with significant non-zero MET are flagged as potential dark matter candidates, however, the challenge of distinguishing such events with those caused by normal matter particles still remains.

4.3 Creating dark matter

Since dark matter events (if they were to occur) are incredibly rare, it means that we would be investing a lot of money and resources for a very low chance of detecting anything. To avoid this, there have been attempts to create dark matter in particle accelerators such as the LHC. If this can be successfully introduced, it would make analysing dark matter much simpler, since samples can be synthesised.

4.4 Evaluation of methods

Each method has its strengths and weaknesses, and the choice of the most effective method depends on the specific dark matter properties being targeted. As discussed LUX-ZEPLIN is one of the most advanced dark matter direct detection experiments and leads in sensitivity for certain WIMP mass ranges due to the large target mass and excellent background discrimination. CDMS is highly sensitive as well, but for lighter WIMPs. LUX-ZEPLIN has a slight edge when it comes to background discrimination due to the liquid xenon medium, whilst collider experiments (indirect detection methods) face significant challenges in this regard.

Indirect detection through colliders, whilst facing significant challenges, remain an essential approach to exploring the broader landscape of dark matter.

Currently, creating dark matter seems to be the least effective method mainly due to limitations with the technology available. Moreover, creating dark matter is based purely on luck; particles are collided with a hope something of interest will arise. It cannot be monitored effectively to attempt to create a specific candidate - it is about being in the right place at the right time and doesn't really follow any logical steps which is what, I believe, makes it the least effective method.

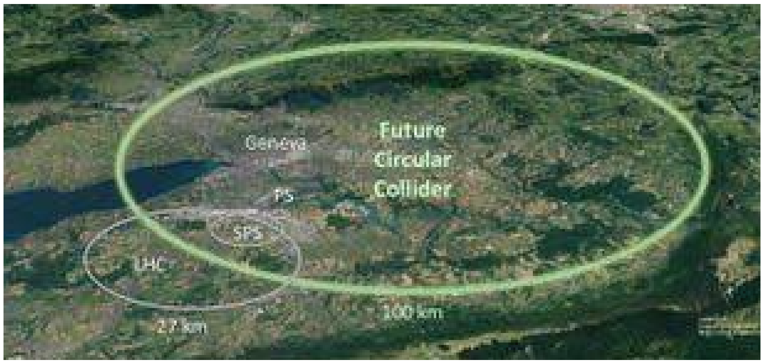
A multi-faceted approach leveraging the strengths of each method will allow us to best succeed in the hunt for dark matter.

4.5 The future of the search for dark matter

Although our current methods of searching for dark matter have been to little avail, several projects are in development to advance this search:

- Whilst creating another detector similar to the LZ with improved sensitivity may appear to be the right path in the hunt for dark matter, there has been research on other new and innovative detectors. For example, the NEWS-G (new experiment with sphere-gas) detector is in development by SNOLAB in Sudbury, Canada. It uses a copper sphere filled with a noble gas that, if ionised by dark matter, will release electrons that can be easily detected. It is different from current detectors in that that it is tailored for low mass dark matter particles. Currently, the NEWS-G operates provisionally as a research project, and a bigger version could be constructed if useful data can be obtained.

- It is theorised that dark matter particles have indeed been created in the LHC. However, they are too light and can escape from the accelerator. To overcome this issue, a new particle collider, the Future Circular Collider (FCC) is being discussed, with the feasibility study set to be completed in 2025. If development begins, it will take until 2070 for the FCC to be fully functioning. The FCC would be a very large scale collider: a 91 km circumference ring (in comparison to the 27km LHC). This would not only make the FCC very useful as a general particle accelerator, but also in the hunt for dark matter.



- The DUNE (deep underground neutrino experiment) program is currently under construction with the first module to start taking data by 2028. This particle detector could assist in the detection of dark matter particles.
- The SuperCDMS SNOLAB (an improvement on the SuperCDMS) was fully installed in late 2023 with operation to start in 2024. This will be more sensitive than past CDMS iterations, so could pave the way for direct dark matter detection.

5 Conclusion

Overall, the hunt for dark matter at this point in time, with the technology available proves to be a very difficult task, especially in terms of sensitivity. It is reassuring that in the future, innovative ideas such as the NEWS-G are being suggested as well as the development of fields with substantial progress such as the SuperCDMS SNOLAB. Whilst the current methods haven't produced any definitive data, they have helped identify which areas are not worth researching, which is still of some use in the long-run hunt for dark matter. With the combination of these, it seems fairly likely that a breakthrough seems a possibility in the near future which would have a huge impact on our understanding of the universe as we know it.

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