Cosmic Ghosts: Hunting for Clues in the Dark Matter Realm

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Abstract

Dark Matter appears as a central and mysterious entity that permeates the cosmos, standing as one of the most perplexing and intricate challenges in physics, overcoming borders and driving the convergence of several scientific fields in an attempt to solve its mysteries. As Dark Matter is by far the most prevalent particle in the universe, we would like to know what exactly makes it up since this would be helpful in understanding the dynamics of galaxies and the development of the universe. In fact, scientists have been meticulously cataloging the stuff in the cosmos for more than 50 years. But in spite of our astounding findings in the field of physics, the puzzle of dark matter, which dates back from 1993 when Zwicky remarked that the Coma cluster of galaxies would not remain bound unless it contains considerably more mass than we can see in stars, has still been unsolved [1]. It is embarrassing to know that 95% of the Universe's gravitating matter is non luminous, and we do not yet know the exact amount, or the nature, of this obviously major component of the physical universe. In this paper, I will outline a thorough overview of the data and scientific details about Dark Matter's astrophysical evidence, candidates, detection methods, and alternative theory, with the goal to provide non-expertised readers an insight and approachable view of the Dark Matter question.

Introduction

We embarked on a quest to answer the most basic questions about our existence. What is it that decides whether we live or die, and which forms the bedrock of reality? In trying to solve this conundrum, we are irresistibly drawn towards the enigmas of dark matter. Non-baryonic dark matter accounts for approximately 23% of the universe's total mass according to what we know about space today; although it has never been seen directly because its presence can only be inferred through gravitational effects on galaxies at large scales — which means that if such an enigmatic entity did not exist, cosmic structures would not have formed due to insufficient gravity pulling things together hence different theories propose that dark matter might consist of some elementary particles yet undiscovered having mass but feeble interactions with normal matter. Astronomical observations lead us into the most remote regions while experiments in particle physics bring us face- to-face with high-energy collisions; all in a bid to reveal this hidden stuff which constitutes most of the material content of our Universe. These particles have influence on large-scale structure through their gravitational attraction, and these are precisely what those new techniques try to detect. This article sets out with an aim at exploring an intriguing puzzle called “dark matter” looking into its invisibility, gravitational impact over space as well as current scientific queries surrounding its nature.

Evidence for Dark Matter

The galaxies spin differently than expected

From the beginning of the 20th century up to now, researchers venturing into space have found out that stars orbiting around the center of our galaxy move at about the same rate as those close to it. It seems that stars are moving faster than they should be able to [2].

$$F = \frac{GMm}{r^2} = \frac{mv^2}{r}$$

Newton's law of Universal Gravitation - the gravitational fields drop off with the square of the distance from the mass producing that gravity - states that objects should be moving much more slowly because the force of gravity decreases with increasing distance. The evidence for this is all of the orbits of planets in our solar system. For example, the two closest planets to the Sun, Mercury and Venus, have the highest velocities when it comes to orbiting around the Sun: 47 km/s and 35 km/s respectively. As we move farther from the Sun, planets begin to move at a slower pace [3].

To illustrate this, let's use the idea of circular motion. In order for an object to move in a circle, it must be supplied with a force that will keep it in that curved path. For an object to travel along circular paths forces are needed. Sometimes we have taken a ball tied it with a string and then rotated this over your head. The string which is between our two hands always pulls towards the middle point or center of the ball. If we spin the ball faster, there will be more tension in the thread. However, gravity performs such a function not only on stars but also galaxies where no strings exist otherwise known as cosmic gravity. Faster stars move; stronger gravitational pull should be exerted by them.

Therefore, a comparable analogy can be applied to galaxies wherein, assuming that the luminous region of a galaxy indicates the location of the majority of its mass, the center of the galaxy houses most of the mass, and the outskirts possess a notably lower mass. Accordingly, objects which orbit a galaxy’s center at a large distance should have lower velocities than those closer in, just like planets behave within our solar system. Yet this inverse square law does not fit with the mass of all visible matter in galaxies, for some reason. To experimentally examine this proposition, researchers scrutinized the incident light originating from a spiral galaxy which is similar to our galaxy - the Milky Way - and graphed the velocities of stars as a function of their displacement from the galaxy's center [3]. Surprisingly, the stars did not conform to the predicted behavior. The motion of stars in the galaxy is about 200 km/s regardless of the distance from its center and too fast for the observed gravity to keep stars in check. The galaxy should have ripped itself apart.

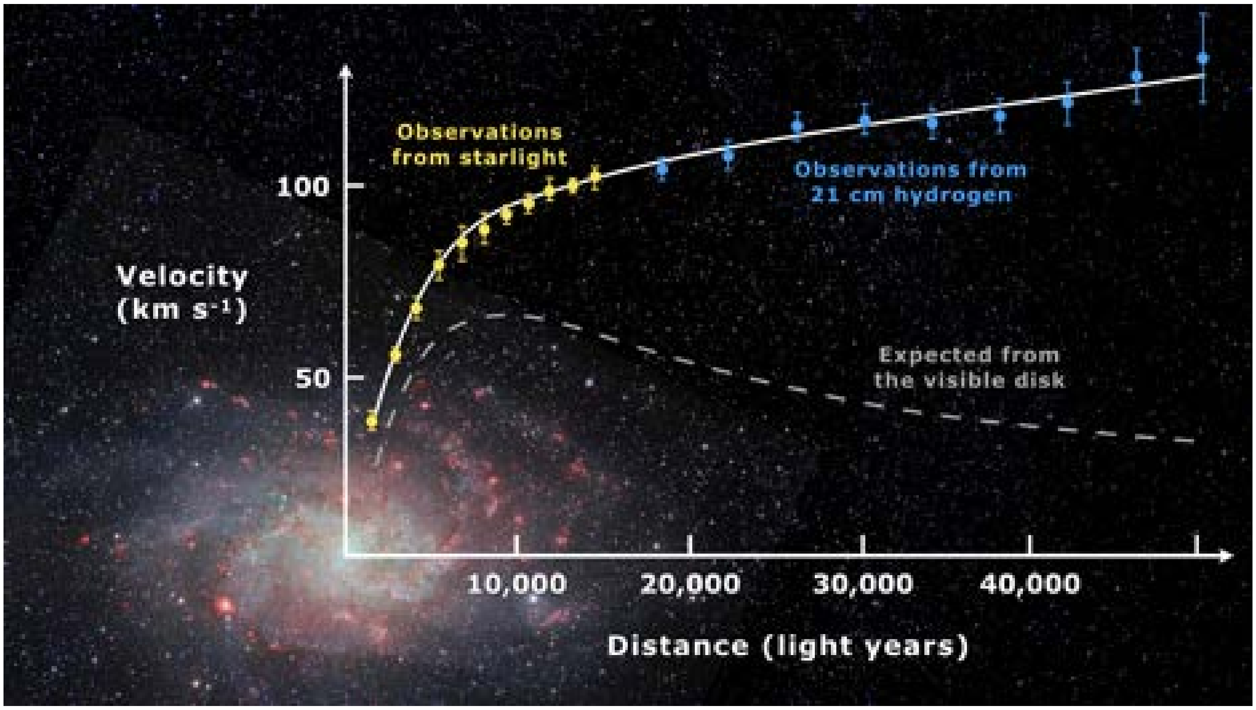


Figure 1 shows the discrepancy of the actual velocity curve (orbital speeds of visible stars or gas in that galaxy versus their radial distance from that galaxy's center), illustrated in yellow and blue points with error bars, of a spiral galaxy that has the same properties as our Milky Way versus the expected one from distribution of visible matter. The discrepancy between the two curves serves as a piece of significant evidence for Dark Matter's presence.

For everything to be sure, scientists established that stars located further from the center moved at considerably higher velocities than anticipated. Such an outcome is only possible if a greater mass exists within the external regions of galaxies than is detectable by us. That's why it was theorized that the absence of observable light emitted by this mass is due to the extra unseen matter or dark matter.

The bending of light

The works that showed astronomical bodies were moving too fast to explain using the known laws of physics and the observed matter are similar sorts of measurements telling a similar story. Still, they are not observations that suggest dark matter is real. In the end, strong evidence for the existence of dark matter finally arrived in the mid-2000s in the form of the Bullet Cluster which is two clusters of galaxies colliding with each other [4]. To bring us to the next piece of very strong evidence for Dark Matter, a technique called gravitational lensing is applied. Thanks to this method, we discovered that there is much more undetectable dark mass in the universe than normal matter that our telescopes can detect.

Gravitational lensing takes place when a massive amount of matter, such as a star, galaxy, or cluster of galaxies, forms an intense gravitational field around it, strong enough to bend light from galaxies behind it, the phenomenon. When galaxies in front of distant sources block their view, gravitational lensing tends to enlarge those sources. Einstein's theory of relativity suggested that matter distorts the fabric of space and time around it, implying that gravity bends light waves, making their path curve around massive objects like stars, galaxies, or even black holes. By way of illustration, imagine placing a bowling ball on the sheet. We can see that the seat is being pulled down by the bowling ball. The ball curves the sheet in the same way that mass curves spacetime. Using this theory, you can determine the mass of an object by observing how much light bends from the star directly behind it. This is shown in figure 2 as a solar eclipse when the moon moves between the Earth and the sun blocking the sun's light for some time. Therefore, stars that are not within our solar system also experience this decrease in brightness as they lie on the same side of the Sun just like during an eclipse. In such a scenario, what happens is that there is nearness between its rays and those from our star. The gravity field of the Sun behaves like a lens which refracts or bends the far away light towards us through its own atmosphere. This makes it seem as if this foreign celestial body is positioned slightly away from where it should be noticed by people living on earth but in reality somewhere else entirely.

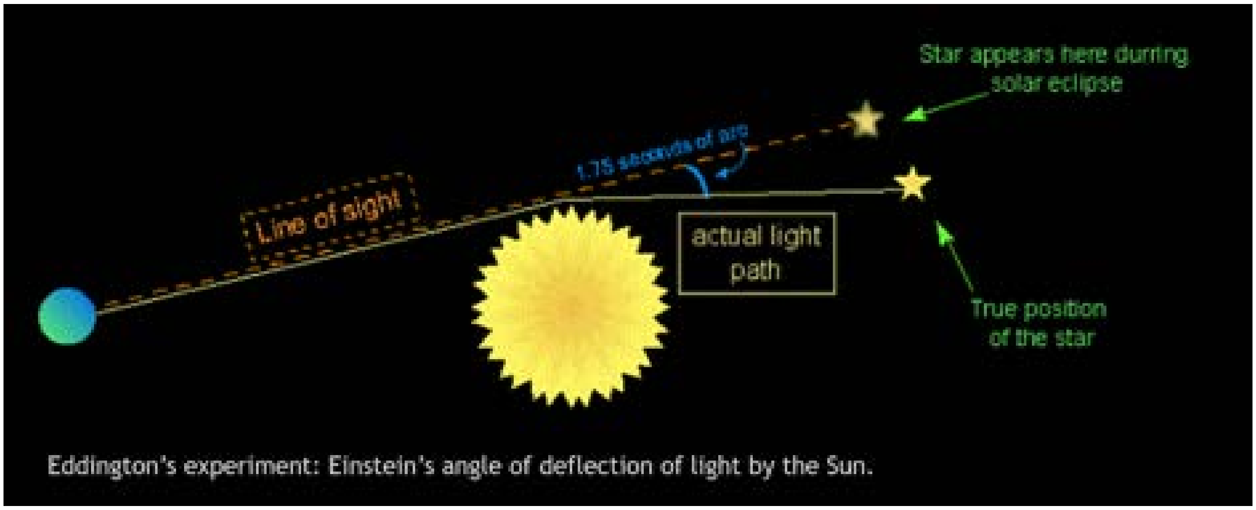


Figure 2: Observation of the gravitational lensing effect. During a solar eclipse, the sun bends light from a faraway star to distort the true position of the star.

We can use gravitational lensing where there is matter and then see whether that corresponds to actually observing matter or not, so that brings me to the next piece of very strong evidence for Dark Matter which is Bullet Cluster. As two large clusters of galaxies collide, gravitational lensing observations reveal that most of the mass is concentrated in regions with little visible light. This discrepancy indicates the presence of dark matter, which does not interact with regular matter and passes through unaffected. What is shown in Figure 3 is the blue clumps passed through very easily and did not interact very much whereas the red slowed down and got stuck in the middle. That's because ordinary matter interacts and gets slowed down as they pass through each other whereas dark matter is not just interacting and just passing straight through. The gravitational maps of the Bullet Cluster further corroborate the need for dark matter by showing that the distribution of matter does not align with the distribution of visible light [4,5].

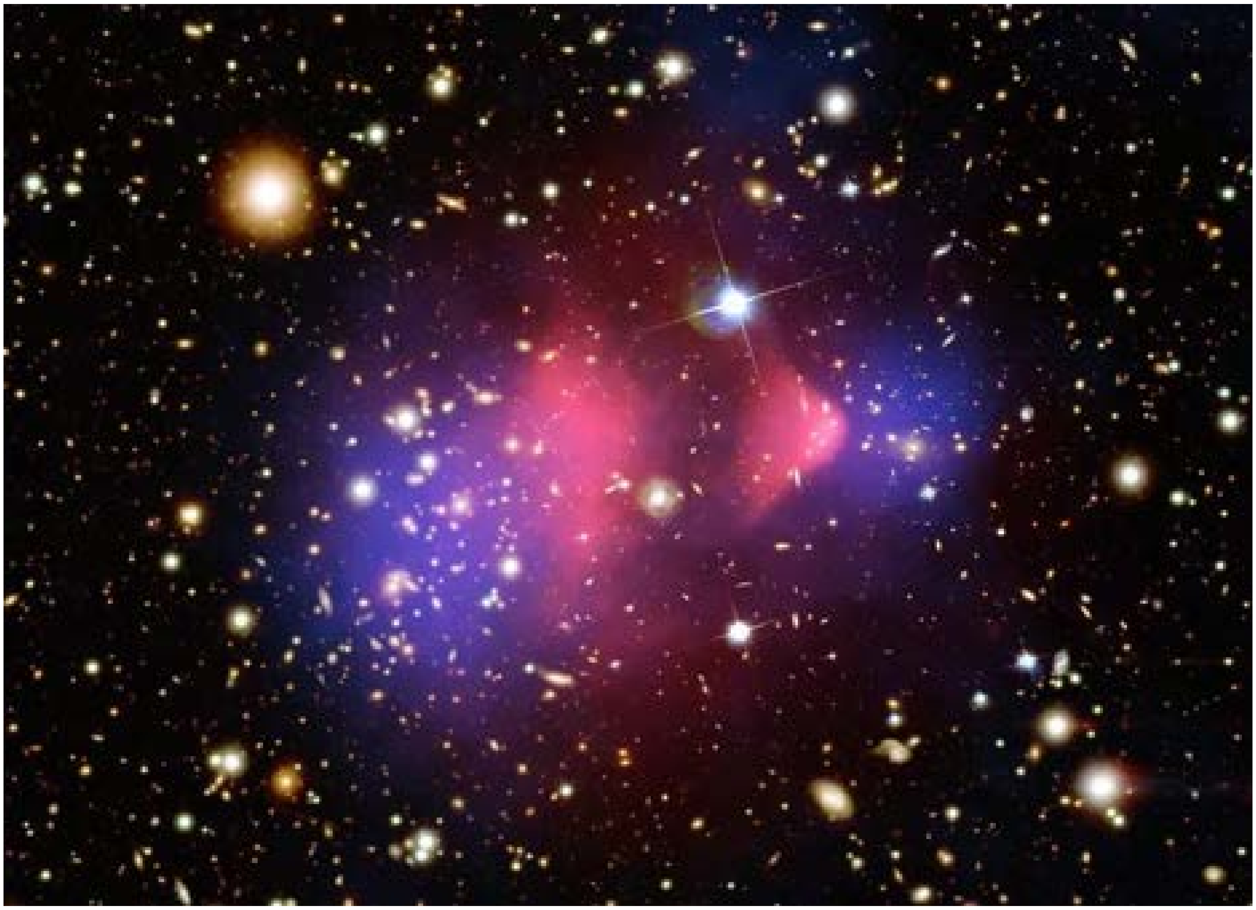


Figure 3 shows the galaxy cluster 1E 0657-56, formed after the collision of two large clusters of galaxies.

Cosmic Background Radiation

Apart from those pieces of evidence mentioned above, there is another compelling proof to explain Dark Matter's existence: precise measurements of the temperature anisotropies in the cosmic microwave background (CMB). The Cosmic Microwave Background (CMB) is the cooled remnant of the first light that could ever travel freely throughout the Universe [4].

Today, the Universe is transparent to light, and the light from distant objects can travel unimpeded through space before reaching our eyes. But it was sometimes different. In particular, during the early universe which is for roughly the first 380,000 years, the photons and energy were abundant, but they were not free to move much. They bounced around and scattered because the universe was so hot then. This means atomic matter that makes up everything we know of is ionized, meaning that both nuclei and electrons are not bound to each other. Thus the atomic component, or baryons, is not electrically neutral, and because the photons form a high pressure fluid, baryons and the CMB photons are tied together to make a "baryon-photon" fluid. This fluid has a high sound speed since the photons provide most of the density and almost all of the pressure. In a region with high initial density, there will be a high pressure in the baryon-photon fluid which will propagate as an expanding spherical sound wave [6]. The Universe had kept expanding and as it expanded, it cooled, as the fixed amount of energy within it was able to spread out over larger volumes. About 380,000 years after The Big Bang, it had cooled to around 3000 Kelvin, and electrons were able to combine with protons to form hydrogen atoms, making the Universe transparent to light and able to reach out. This process is known as recombination. Recombination allowed photons to decouple from matter and freely stream through the universe. The acoustic density waves “froze” in place during recombination or in the other word, relics of the photon-baryon fluid at the surface of the last scattering, where photons from recombination have come to Earth, are the observed CMB photons [7].

Thanks to CMB, we can examine to figure out exactly what temperature the universe’s background radiation is. The fact that the black body spectrum is almost perfect, suggesting that the temperature is evenly distributed. In other words, the universe is thought to be very isotropic (the same in all locations) and homogeneous (the same in all directions) when the CMB was formed. The isotropy and homogeneity have manifested in the universe we see today where the average density of galaxies is the same throughout the universe and does not change much with distance or direction. Nonetheless, the CMB actually exhibits very little variations in both temperature and polarization across various sky locations with a variation of 0.00003, or roughly 1 in 100,000, and these small temperature fluctuations are called anisotropies [8]. These fluctuations originated from density variations in the early universe. There were areas that were less dense (underdense) and others that were marginally denser (overdense). Scientists frequently utilize color coding to depict temperature fluctuations in their CMB images. In figure 4, regions with a somewhat greater matter density than normal are referred to as overdensity regions (blue-coded). They draw in more stuff because of their higher gravitational attraction due to gravity’s attractive nature. As a result, they became even denser over time [9]. Increased matter equals increased gravitational potential energy. They are therefore connected to higher energy. On the other hand, less matter accumulates in underdensity zones (shown in red), which have a little lower matter density and a less gravitational force. Less matter translates into less energy. They are therefore linked to reduced energy.

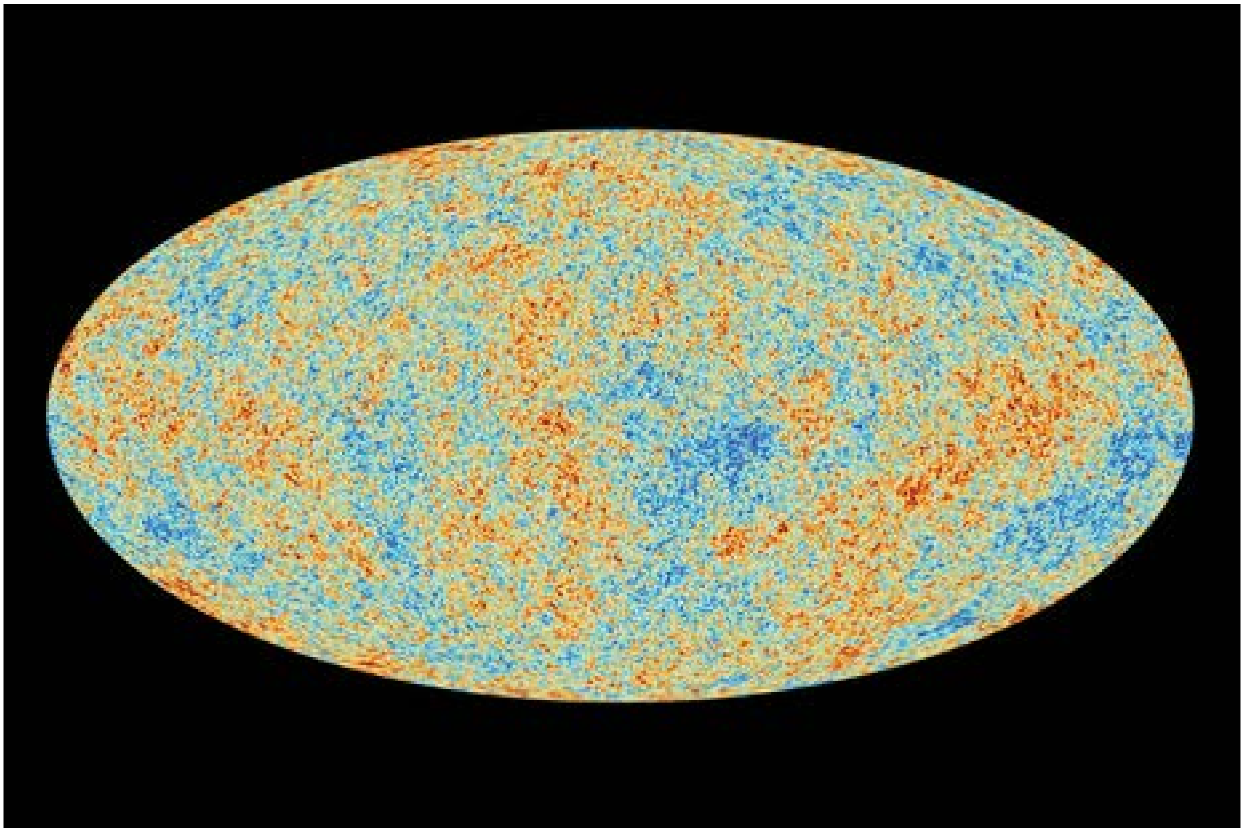


Figure 4: Planck's view of the cosmic microwave background. The spots on the map correspond to photon energies at the time of the last scattering of photons by electrons.

These overdense regions served as the seeds for the formation of galaxies and other cosmic structures because overdense regions will undergo gravitational collapse to form regions of significant overdensity. For the observable distribution of galaxies throughout the cosmos to have expanded from the density variations during the recombination event. These fluctuations need to be around 1% of the mean density; otherwise, the large-scale formations that we observe today would not have developed. However, the CMB shows remarkable uniformity over the sky (up to more than a part in 10^5 compared to growth by a factor 10^3 measured since then), which is consistent with a uniform baryon density during recombination [10]. In other words, the possible explanation for galaxy formations cannot not only be the fluctuations in baryon density at recombination because if we consider only baryonic matter, its gravitational pull would not be sufficient to initiate the collapse of these overdense regions into galaxies and baryonic matter interacts electromagnetically, leading to pressure forces that can counteract gravitational collapse. As a result, it is theorized that dark matter exists as an additional component of this theory [10]. Dark matter, however, doesn’t experience electromagnetic interactions or pressure. It only interacts via gravity. The gravitational force necessary for initiating a collapse in over-dense areas and giving birth to structures like galaxies comes from this invisible material. During their gravitational fall towards each other, these regions attract baryonic matter too, which then condenses into small dense pockets filled with stars or any other cosmic bodies eventually [11].

Thus, to confirm the presence of dark matter, scientists conducted measurements of the angular anisotropy spectrum of the Cosmic Microwave Background (CMB) using Planck data [12]. These observations shown in Figure 5 provide valuable information about the universe — as well as baryon density — revealing peaks. The spacetime geometry exhibits peaks at odd multiples (with the first peak defining the spatial curvature) while some pairs have specific ratios, e.g., (2:3), that give more clues on baryonic contribution. The measurements are highly consistent with expectations from cosmological models featuring the dominant component of matter being dark matter. The ratio of odd peaks to even peaks (such as the second and third peaks) provides insights into the baryon density. While the second peak (odd) corresponds to the first acoustic oscillation mode, the third peak (even) corresponds to the second acoustic oscillation mode. The ratio of their heights reflects the balance between baryonic matter and dark matter. A higher ratio indicates a higher baryon density relative to dark matter. Unlike baryons, dark matter does not feel electromagnetic pressure during acoustic oscillations since it doesn't interact via electromagnetism; therefore, the third peak is responsive to total matter density (baryonic plus dark). Sensitivity of the third peak to the total mass density, and particularly the contribution from the dark matter is due to absence of any feedback mechanisms which tend to keep radiation and matter in step with each other.

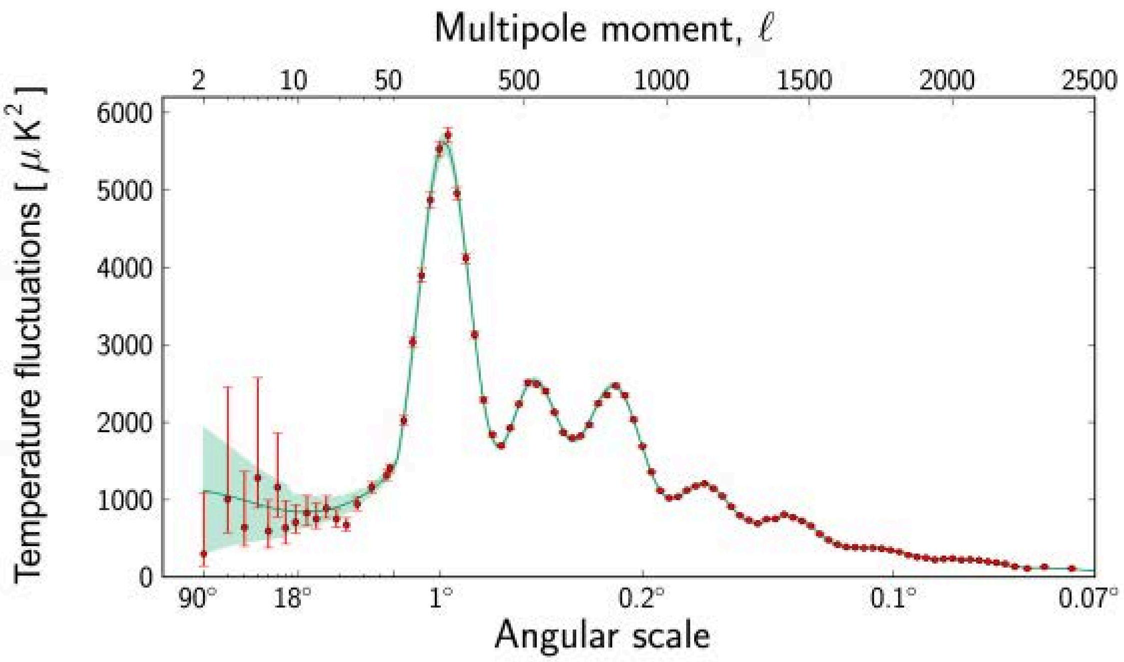


Figure 5: The CMB power spectrum versus the multipole moment l and the angular size θ. The curve shows the theoretical prediction of the power spectrum, while the red points represent the Planck data as of March 2013

What dark matter could be?

One thing all the evidence for dark matter stated in the previous section has in common is that we only discovered its presence by its gravitational pull on the universe, as seen in the orbits of stars and galaxies, in the way light bends around galaxies and clusters, in the clumpiness of the cosmic microwave background radiation. The concept of dark matter was developed because the gravity of today's visible matter could not provide an adequate explanation for the formation of mass in the early universe. Many things were once thought of as possible explanations, such as black holes - which attract matter but don't emit light and are detected by gravitational lensing - or failed stars - or even stranger so-called "compact objects" - hiding out in a galaxy's halo, having large mass but not much light. However, scientists are still mystified by dark matter as to its nature. In short, all of these explanations were not sufficient to explain the quantity of dark matter required. According to modern day astrophysicists, dark matter is likely to be composed of subatomic particles with properties that differ from protons and neutrons, namely non-baryonic matter.

Dark matter's properties

The Standard Model is one of the most popular theoretical frameworks that describes the behavior of a vast family of particles. These particles are what constitute everything we see in space. They interact among themselves through three forces: strong nuclear force, weak nuclear force, and electromagnetism; or rather put these three forces can be thought of as languages which particles use to talk to each other [13].

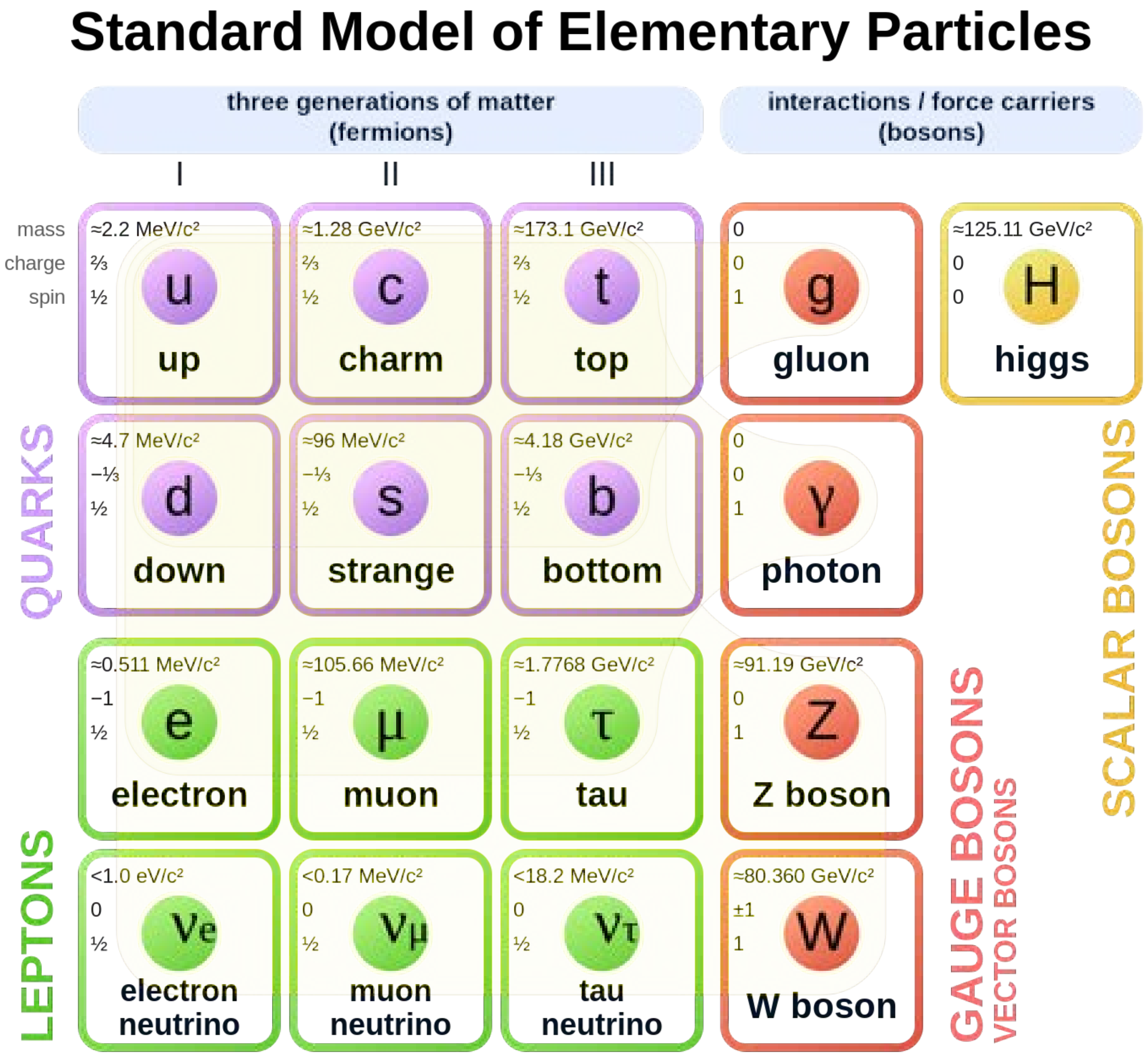
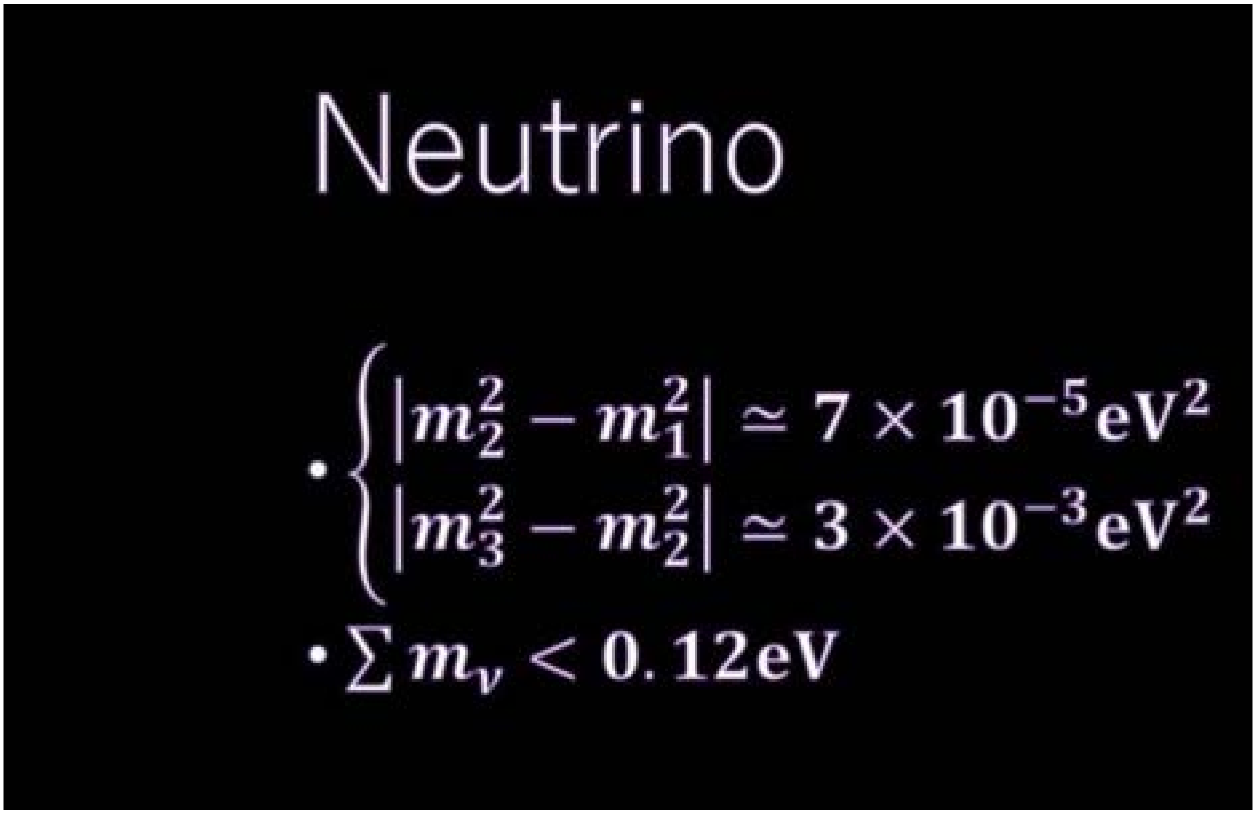


Figure 6 shows the chart of the Standard Model of Elementary Particles. There are 2 main types of fundamental particles: fermion and boson. Leptons (which have six members) and quarks (also have six members) are the two families of fermions. Protons and neutrons contain up and down quarks, which belong to the quarks family. Each of the twelve fermions has a spin value of ½. They interact with one another through fundamental forces: weak interaction with Z and W bosons, electromagnetic force with photons, and nuclear force with gluons.

Most matter particles in the Universe are either too light to become dark matter or have lifetimes shorter than the age of our universe thereby making any evidence for dark matter beyond SM impossible [14]. The condition for a dark matter particle is that it should be collisioness [15]. If it interacted, then giant regions of dark matter would lose energy in those collisions and contract. They might collapse into dark matter galaxies and dark matter stars. But no - dark matter seems to stay puffed up in gigantic halos surrounding the much more concentrated clumps of visible matter [16]. The fact that dark matter forms those giant halos at all tells us something very important. It gives dark matter a temperature. We refer to such dark matter as “cold” [15]. This is because as the Universe expanded and cooled, particle interactions decreased. At this time, Dark Matter particles decoupled from the thermal bath, effectively “freezing” their velocities, and these slow-moving dark matter particles could then gravitationally attract each other to clump together. Over time, these clumps grew, forming those massive halos. If dark matter particles were too fast (highly relativistic), They would be able to elude the attraction of crowded areas and the development of small-scale structure, resulting in structures that differ from what is seen [16]. Another condition for a dark matter particle is that it cannot communicate via electromagnetic or must have very weak electromagnetic interactions because it does not emit light, thus the term "dark”. Besides, it does not absorb light, otherwise we would be able to detect it when it blocks light from the more distant universe. From this, we may conclude that dark matter is both absolutely dark and perfectly transparent, implying that it, like the neutrino, is electrically neutral [16, 17].

Dark Matter’s candidates

For a long time, people thought the neutrino might be dark matter - being neutral and the most abundant known particle in the universe [18]. With the emergence of Super-Kamiokande leading to the discovery of neutrino oscillations, the following connections regarding the three types of neutrino masses have been established. In this figure 7, m1, m2, and m3 indicate the eigenvalues of mass corresponding to electron neutrinos, muon neutrinos, and tau neutrinos, respectively. If the neutrino masses follow a hierarchical pattern similar to quarks, even the heaviest among them, m3, would be approximately 0.05 eV, which is insufficient to account for dark matter. But if the neutrino mass is nearly degenerate then it could reach several eV [19]. A strong constraint on neutrino mass comes from cosmological considerations. The shape temperature fluctuations in the cosmic microwave background spectrum changes depending on whether or not there are any massive ones present so by Planck satellite observations combined with other cosmological probes we can put an upper limit at 0.12eV for total mass of three lightest species. Therefore they may not fulfill the role of dark matter.



Neutrino

- $\begin{cases} |m_2^2 - m_1^2| \simeq 7 \times 10^{-5}\mathrm{eV}^2 \\ |m_3^2 - m_2^2| \simeq 3 \times 10^{-3}\mathrm{eV}^2 \end{cases}$
- $\sum m_\nu < 0.12\mathrm{eV}$

Figure 7 shows the corresponding masses of three types of neutrino.

Supersymmetry is an expansion of the standard model that suggests every ordinary particle, whether it is matter or a force carrier, has a twin or counterpart on the opposite side [13]. Each matter particle or fermion possesses a supersymmetric force carrier or boson, and every boson has its fermion. These supersymmetric particles are anticipated to be much heavier compared to their standard model counterparts, which may account for why we haven't observed them in our particle accelerators. However, it is conceivable that they were created during the enormously energetic early universe, and the remnants from that time might still be having an impact. The simplest form of dark matter resulting from supersymmetry is known as a "neutralino." It is a combination of the electrically neutral superpartners of the Z boson, photon, and Higgs particle [13]. In some models, these neutralinos represent the lightest possible supersymmetric particles referred to as "LSPs,". Normally, heavy objects tend to decay into lighter ones, but if these particles cannot decay into standard model particles, they would remain stable and have a long lifespan, making them almost ideal as dark matter particles.

Different types of supersymmetry offer various candidates for dark matter, such as the counterparts of neutrinos or gravitons, referred to as "LSPs." These particles have a remarkably similar mass to the expected mass of a specific type of dark matter, leading some to argue in favor of supersymmetry [20]. This occurrence, often known as the "WIMP miracle," requires clarification on what a WIMP is. The WIMP, or "weakly interacting massive particle," is a general description assigned by physicists to dark matter particles, including supersymmetric ones like the neutralino. The concept of the WIMP arose independently of specific WIMP candidates, signifying particles that are both massive and weakly interacting. The massive aspect is self-evident, as it allows a particle to contribute significantly to the universe's mass and maintain a slower velocity, making it "cold" [20]. Weak interaction, as we previously discussed, helps sustain the expanded form of dark matter halos. To explain, shortly after the Big Bang, particles and their corresponding antimatter counterparts were constantly coming into existence, extracting energy from the chaotic radiation of that era. When these particles encountered their antimatter partners, they would annihilate, releasing the borrowed energy. As the universe cooled down, this process ceased. The result was a universe filled with particle-antiparticle pairs that gradually annihilated over time. Nevertheless, certain particles may not have had the chance to encounter an antimatter partner before being carried apart by the universe's expansion. Particles like electrons or positrons were highly interactive due to the electromagnetic force, consequently finding each other too easily. These particles didn't experience sufficient expansion to separate them, resulting in the majority annihilating. However, WIMPs, with their extremely weak interaction, had a higher chance of evading their antimatter counterparts, potentially allowing numerous WIMPs to survive to this day. The strength of this interaction aligns with that of the weak interaction. WIMPs solely interact through the weak force or something even weaker. This suggests the presence of an entire ecosystem of particles conducting their mysterious activities throughout the universe, interacting via dark forces, all involving oscillations within their obscure quantum fields, perhaps exhibiting their complexities and diversities [21].

Searching for Dark Matter

Several tests have been conducted to detect the millions, if not billions, of dark matter particles that are thought to be flowing through the Earth every second. Over the years, scientists successfully developed a couple of methods of detecting via special and complicated experiments. There are now three main ways to find dark matter: in particle accelerators, by direct detections of scattering in terrestrial detectors, and by indirect detection of products from dark matter particle annihilation in the galactic halo.

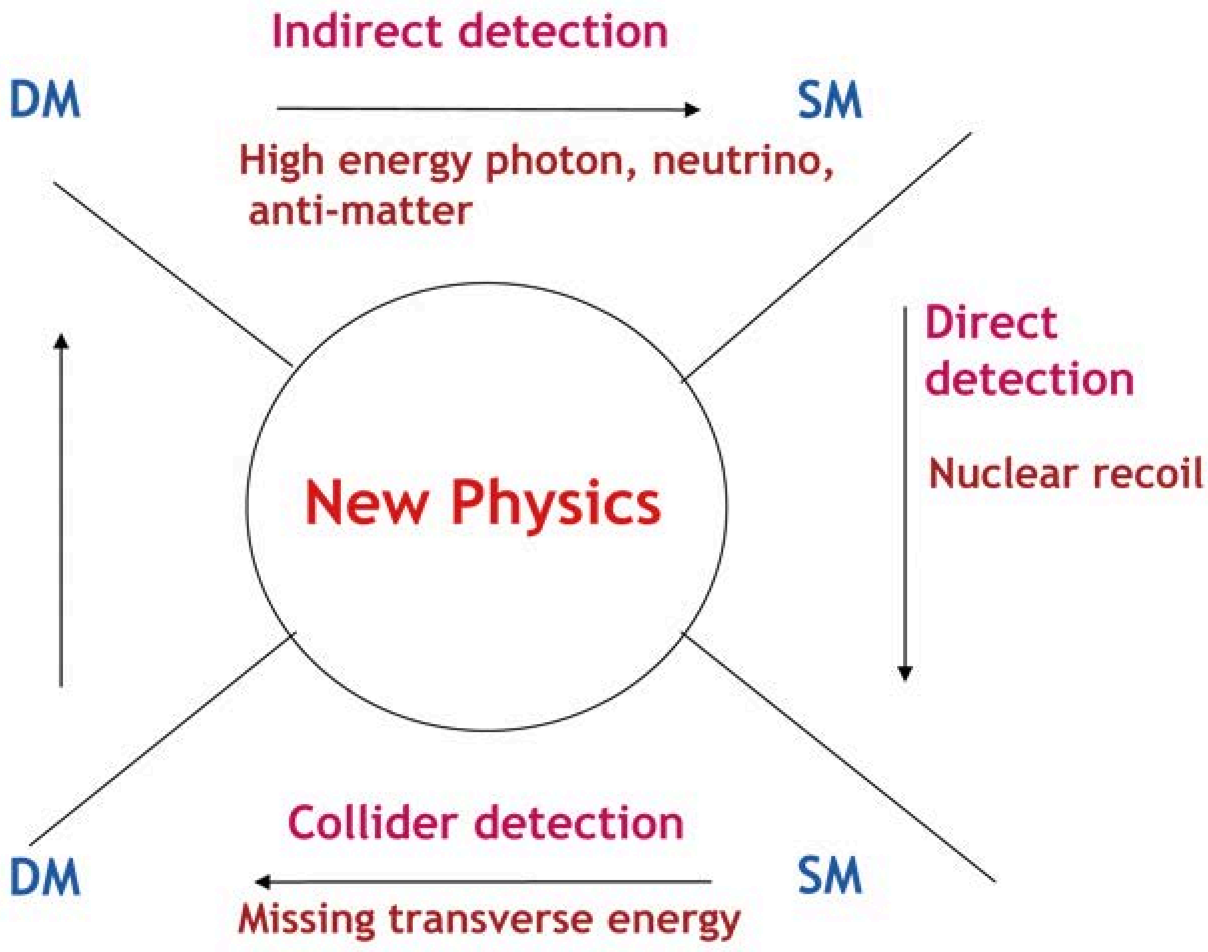


Figure 8: The three main methods of detecting Dark Matter. From the right to the left, one can create dark matter particles in collisions by accelerating ordinary particles to a specific high energy. In the direction from the top to the bottom, dark matter particles can be elastically scattered off from normal particles, and by picking up the signals produced by this scattering, Dark Matter can be directly detected. In the direction from the left to the right, two dark matter particles can collide with each other and annihilate, producing a pair of standard model particles.

Particle Colliders

By colliding standard model particles and searching for events with missing energy or transverse momentum, it is possible to infer the existence of a dark matter candidate. As shown in the figure we can find dark matter much like scientists conduct experiments at Large Hadron Colliders, such as ATLAS and CMS [22, 23].

Einstein's most well-known equation, $E=mc^2$, states that one may create more massive particles (with a mass m) with energy (E) that is approximately 14,000 times greater than a proton's rest mass. In the same manner that proton-proton collisions produce the Higgs boson, it is hoped that enormous dark matter particles can be created at the LHC by colliding known particles.

As their name suggests, Dark Matter particles lack interaction between Dark Matter and ordinary matter. Thus, the primary marker of dark matter production at the LHC, conducted in ATLAS searches, is the existence of invisible particles in proton-proton collisions. The main signature of a Dark Matter particle’s existence in proton-proton collisions from the LHC is called ‘Missing transverse momentum’ [24]. According to one of the main classical physics principles - momenta conservation - the total momentum before the collision must be equal to the total momentum after the collision. Similarly, because protons move parallel to the LHC beams before a collision, the resulting particles’ total transverse momenta also have zero net momentum in the transverse direction [23]. Still, it is possible that unseen particles' momenta were neglected if the total transverse momenta of visible particles do not equal zero. This transverse momentum that was lost is referred to as "ETmiss." The LHC looks for dark matter collisions with high ETmiss values, wherein dark matter is produced together with other visible particles from the Standard Model, such as electrons, muons, or tau leptons, or photons, quarks, or gluons (creating particle jets). Because it depends on accurate measurements of other particles in the collision, ETmiss is challenging for physicists to detect DM [24].

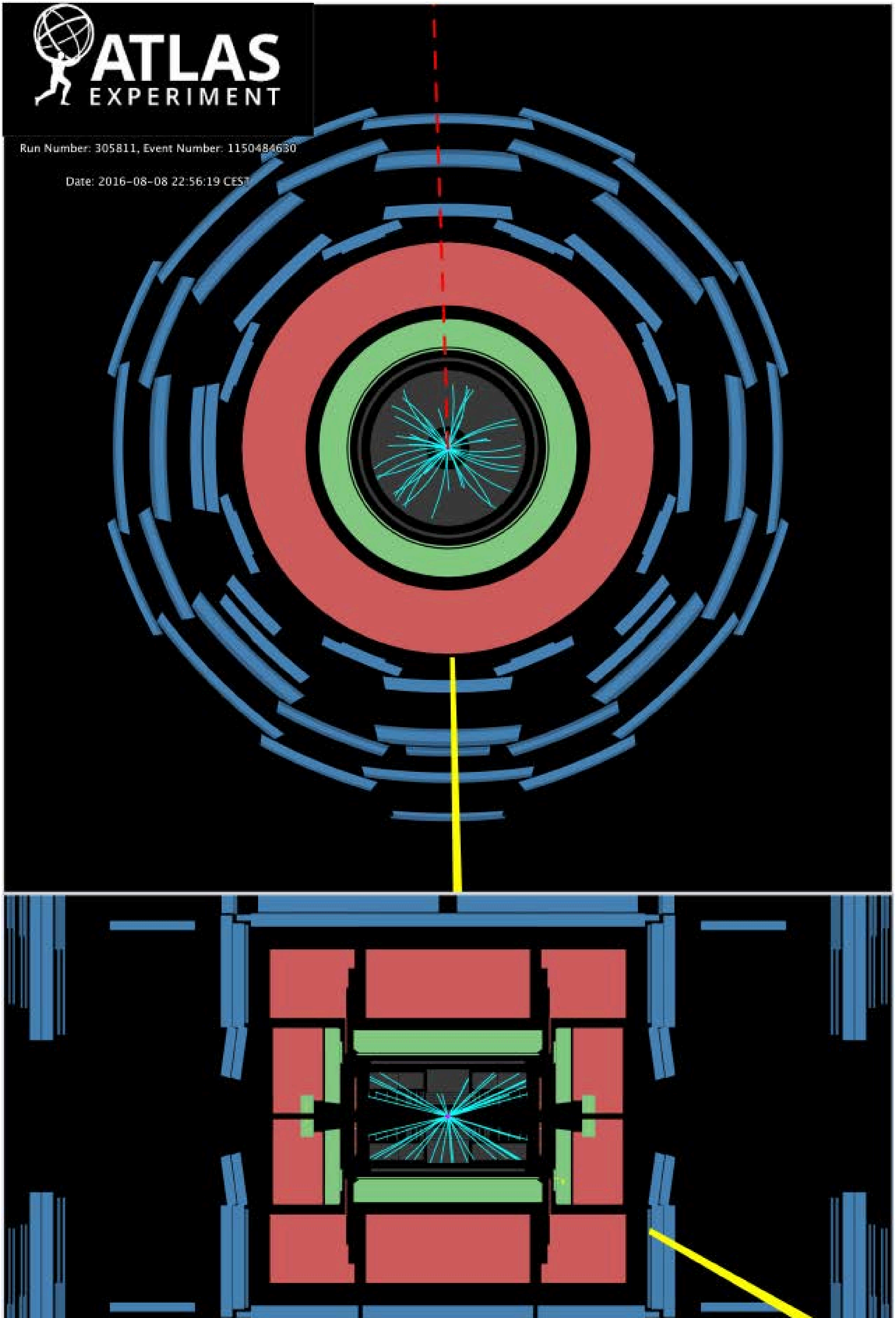

ATLAS
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Figure 9: A visualization of a photon and ETmiss event is shown in the ATLAS detector. A photon with transverse momentum of 265 GeV (yellow bar) is balanced by a ETmiss of 268 GeV.

Direct and Indirect Method

An important aspect regarding collider searches for dark matter that needs to be stressed is the fact that colliders generally speaking offer a complementary and important probe for dark matter, but they cannot determine if what they see is the dark matter of the universe, since any neutral particle that decays outside the detector can be seen as missing energy. Only direct and indirect detection methods provide a way to confirm.

Direct method

Direct detection aims to detect recoils from interactions of dark matter particles with target nuclei in detectors. WIMPS detection ooffers the possibility of directly detecting dark matter particles. As the WIMP is electrically chargeless, it will generally elastically scatter off the atomic nucleus rather than interact with the atomic electrons.

In the case of WIMPs, the nuclei can be observed through three different signals, depending on the detector technology in use. These signals can be either used separately or combined two of these signals. However, a combination of two such signals turn out to be powerful since the relative size of the two signals - the amount of measurable energy that is produced by a particle interacting with the detector - depends on the type of particle. To clarify, in this context, WIMPS, supposed to interact very weakly, is to interact with matter through the weak nuclear force or something even weaker. This means they are more likely to interact with the nucleus of an atom rather than the electrons. Nuclear recoil is less ionized. Electronic recoils, on the other hand, occur when a particle (like a gamma or beta particle) interacts with the electrons in the atom. Thanks to the dependence on the type of particle of size signal, the search for the low-energy recoil of nuclei that have interacted with dark matter particles is distinguished for the electronic recoil [25].

Specifically, in the figure 8, for ionization signals, germanium detectors or gasses are utilized, whereas scintillation can be recorded for crystals and noble-gas liquids. At mK temperatures, cryogenic bolometers are used to gather phonons generated in crystals. In tests with superheated fluids, nucleation processes are also caused by heat signals. Detectors that investigate discrimination power by measuring two signals include double-phase noble-gas detectors for charge and light read-out, scintillating bolometers for phonon and light detection, and germanium or silicon crystals for phonon and charge. Moreover, scintillation detectors are used in the DAMA/LIBRA experiments. They are the only direct detection experiment that has produced any good results thus far. Their findings indicate a dark matter signal that varies with the season, which is to be expected given that the experiment's dark matter density would fluctuate as the Earth revolves around the Sun [26, 27]

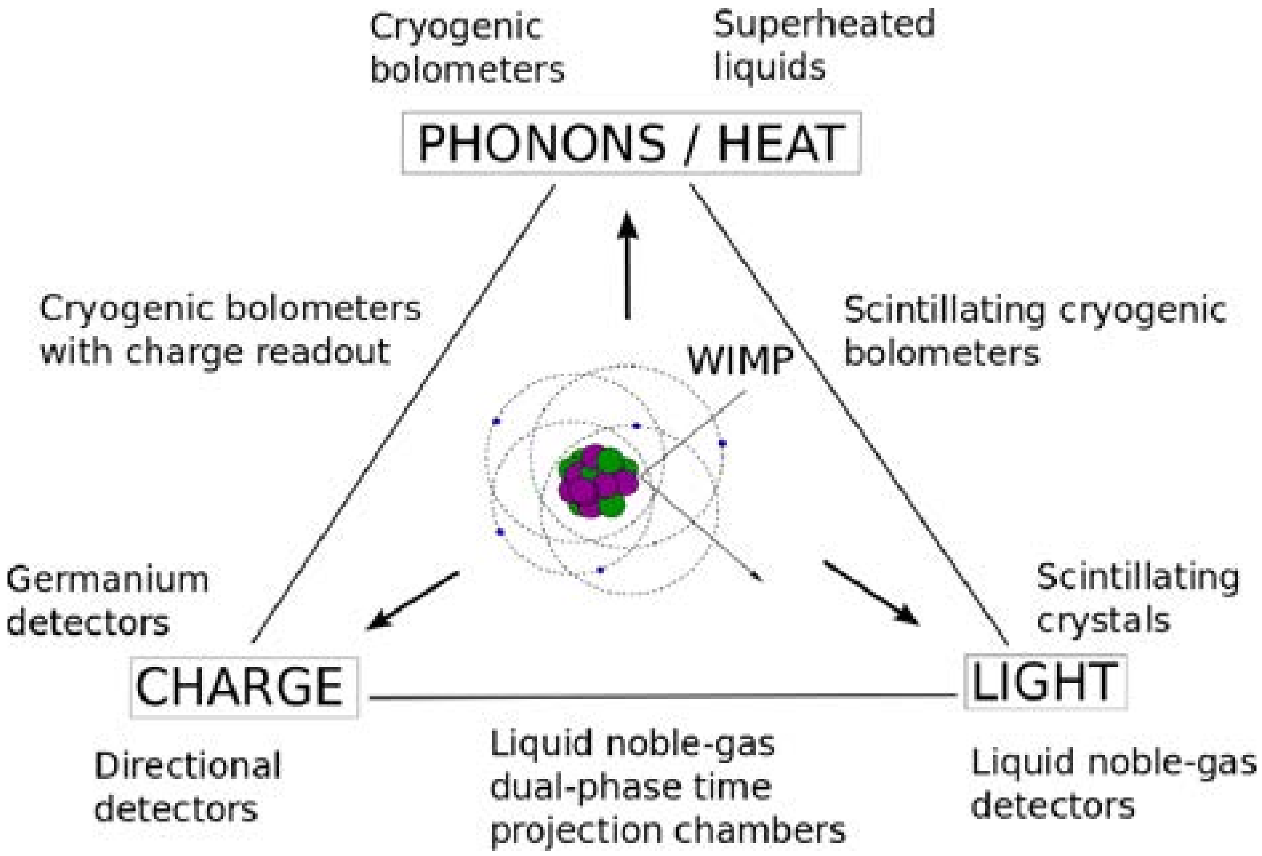

Figure 9 shows a scheme of the possible observables, as well as the most common detector technologies.

Four years ago, we developed and tested the LUX-ZEPLIN, also known as the LZ detector, which is one of the largest and most sensitive WIMP detectors ever made, to serve the purpose of a direct method.

Looking at the figure 9, LZ's heart comprises a reservoir containing an impressive 7 tons of liquid xenon. If a particle traverses the tank and collides with a xenon nucleus, there are two distinct phenomena that occur: a quick flash of scintillation light and a delayed flash of electroluminescence. The light signals are detected by 494 photomultiplier tubes [28], which are positioned at both the top and bottom of the tank.

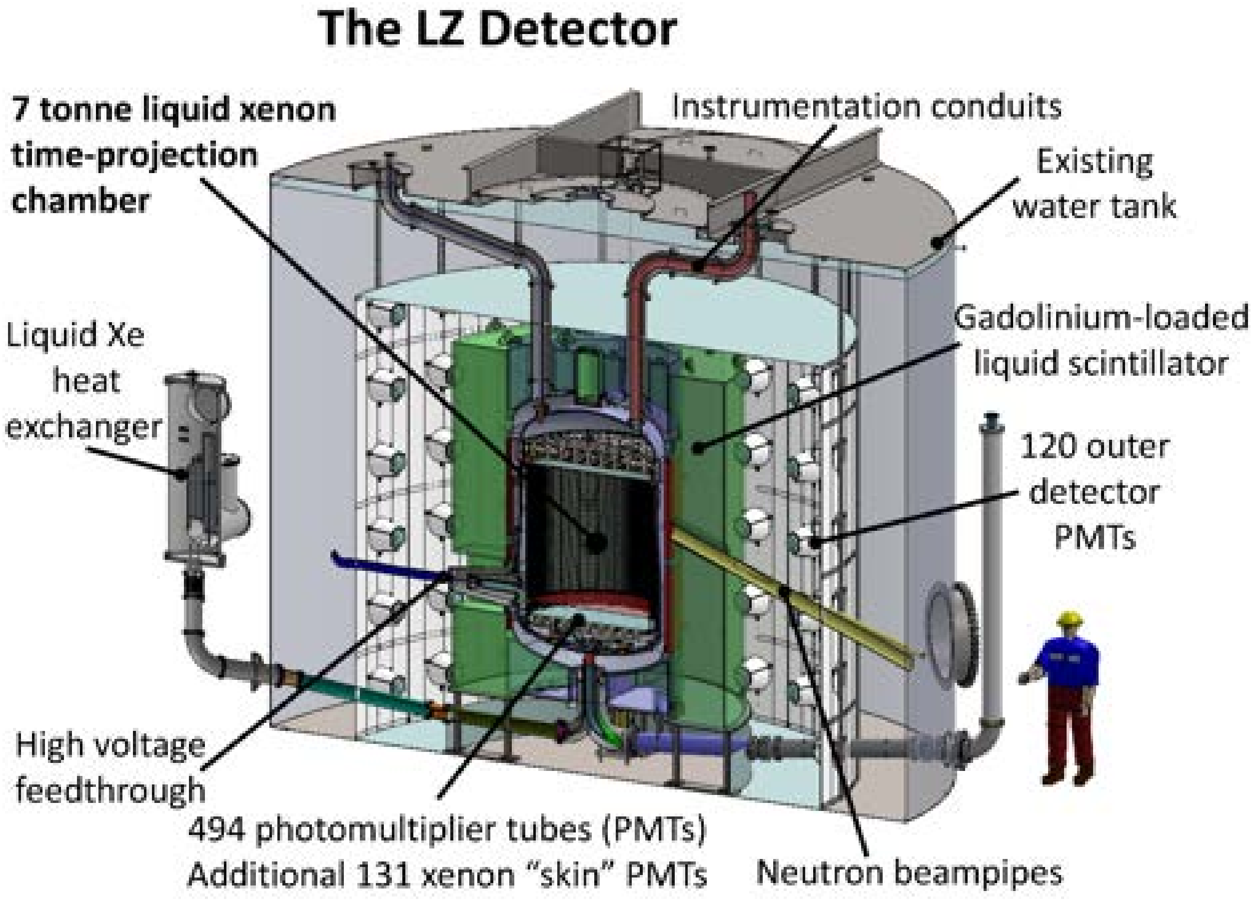

Figure 10 shows the mechanics of the LUX-ZEPLIN Dark Matter experiment.

The process begins when the xenon emits a luminous burst, and concurrently, it releases electrons that traverse an electric field, ascending to the uppermost region of the tank where they generate a secondary burst of light. A Weakly Interacting Massive Particle (WIMP) will produce a distinctive amalgamation of these bursts, which will be detected by nearly 500 light-sensitive tubes. However, to discern a potential WIMP signal, the LZ scientists must confront a considerable amount of background noise. This noise encompasses undesired signals originating from cosmic rays originating from space, as well as gamma rays and neutrons released during natural radioactive decay in the environment and detector materials, so the core of the detector will be encompassed by multiple layers designed to minimize this noise. Initially, the xenon will be purified to an extraordinary degree, eliminating any traces of radioactive krypton. Subsequently, only the innermost 80 percent of the purified xenon within the tank will be utilized for dark matter detection, while the remaining 20 percent will function as a radiation shield. An additional thin layer of xenon, referred to as the xenon "skin," will reject signals originating from gamma rays and neutrons. The tank housing the xenon will be constructed from ultraclean, medical-grade titanium, which generates minimal background signals. This titanium tank will be situated within a larger tank filled with a liquid that, akin to the xenon skin, detects gamma rays and neutrons. Both of these tanks will be enclosed within a third tank containing 70,000 gallons of water, serving as an outer radiation shield.

Indirect method

Dark matter cannot only be detected directly in dedicated experiments searching for nuclear recoils from the scattering of dark-matter particles or produced in particle accelerators such as the LHC, but it can also reveal its existence indirectly. In contrast with direct detection techniques where the interaction of dark matter particles with a suitable target is searched for, the term “indirect” refers to those methods linked to the products of interactions of Dark Matter candidates gravitationally accumulated in cosmological objects. Accumulation of dark matter are expected in the galactic core, dwarf spheroidal galaxies, or galaxy clusters because they are thought to be the regions with high density of dark matter

In order to detect signatures from these regions with high density of dark matter, the dark matter particles need to be able to annihilate between themselves or decay. Because dark matter seems to be so stable, most indirect searches for it focus on looking for signs of dark matter particles annihilating each other rather than decaying [29]. Dark matter annihilation is a process where two dark matter particles collide and destroy each other, converting their mass into other particles. The particles after being annihilated, they will convert their mass into energy, and this energy can create new particles. The specific particles that are created depend on the properties of the original particles and the amount of energy involved. If dark matter is thermally weakly interacting massive particles (WIMPs) then it may produce observable signals when it self- annihilates. Self annihilation is exactly what it sounds like, like two identical but opposite forces meeting, the result is an explosion of energy and particles. In figure 10, two WIMP self -annihilate and turn into quark, lepton and other particles that we are familiar with. These unstable particles will rapidly decay and turn into more stable particles, such as positrons and electrons, protons and antiprotons, neutrinos, and photons, etc [29].

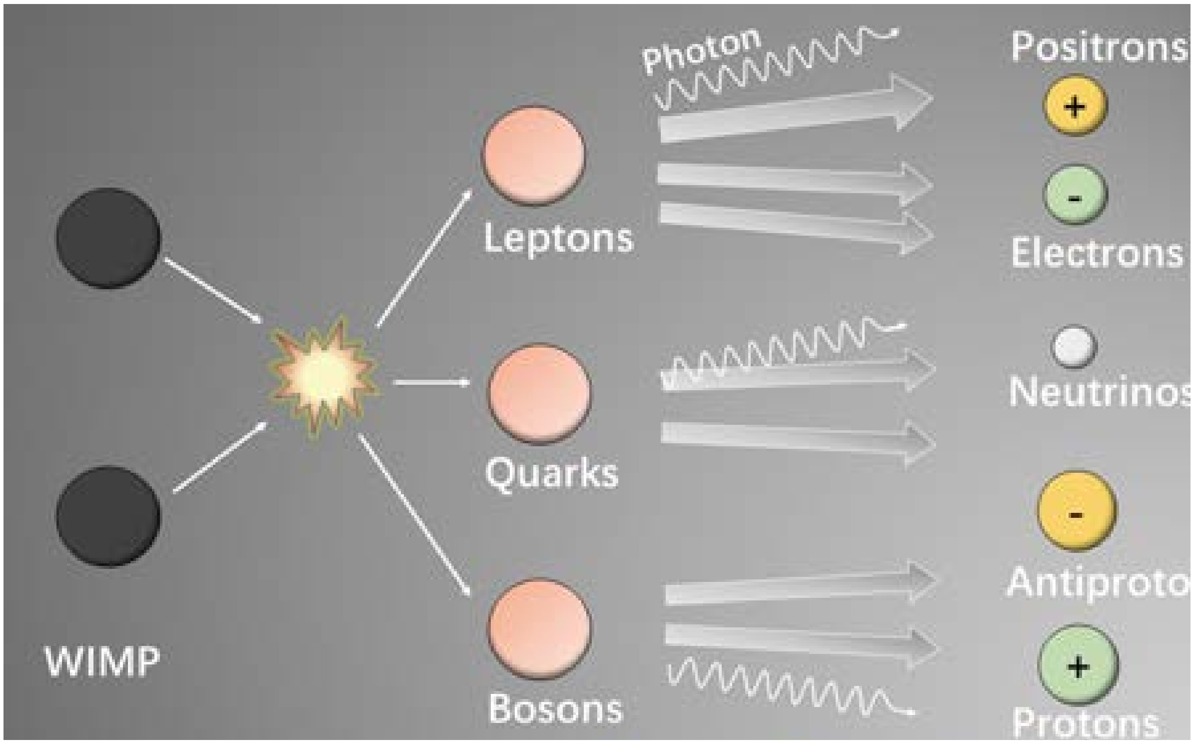

Figure 11: Principle of self annihilation of Dark Matter particles.

Indirect detection of dark matter involves studying gamma rays, which have unique properties that make them ideal for studying dark matter annihilations. Gamma rays travel in straight lines, allowing us to trace them back to their origins, like a cosmic breadcrumb trail [36]. This helps us find places where dark matter might be annihilating, even in distant galaxies or galaxy clusters. The energy of gamma rays from dark matter annihilation is limited by the rest mass of the annihilating particles, meaning the energy cannot exceed the mass of the particles; as dark matter particles are thought to be heavy, gamma rays with high energy (in the GeV and TeV range) are expected to be detected, matching the energy range where dark matter signs are expected [30]. To visualize, picture yourself in a completely black room with no light at all. But you hear things, like footsteps or whispering, and you fear there's someone else in the room. It's too dark to view the individual clearly, yet these oblique cues suggest that they are there. Dark matter doesn't emit light, hence we are unable to observe it directly. However, the cosmic "sounds" it produces allow us to "hear" it. Particles of dark matter may "whisper" when they collide, releasing weak signals similar to gamma rays. Currently, indirect gamma-ray dark matter detection is developing extremely quickly, mainly because of the Fermi-LAT space detector's successful operation and the advanced plans for a very large imaging air Cherenkov telescope array, which will replace the HESS detector.

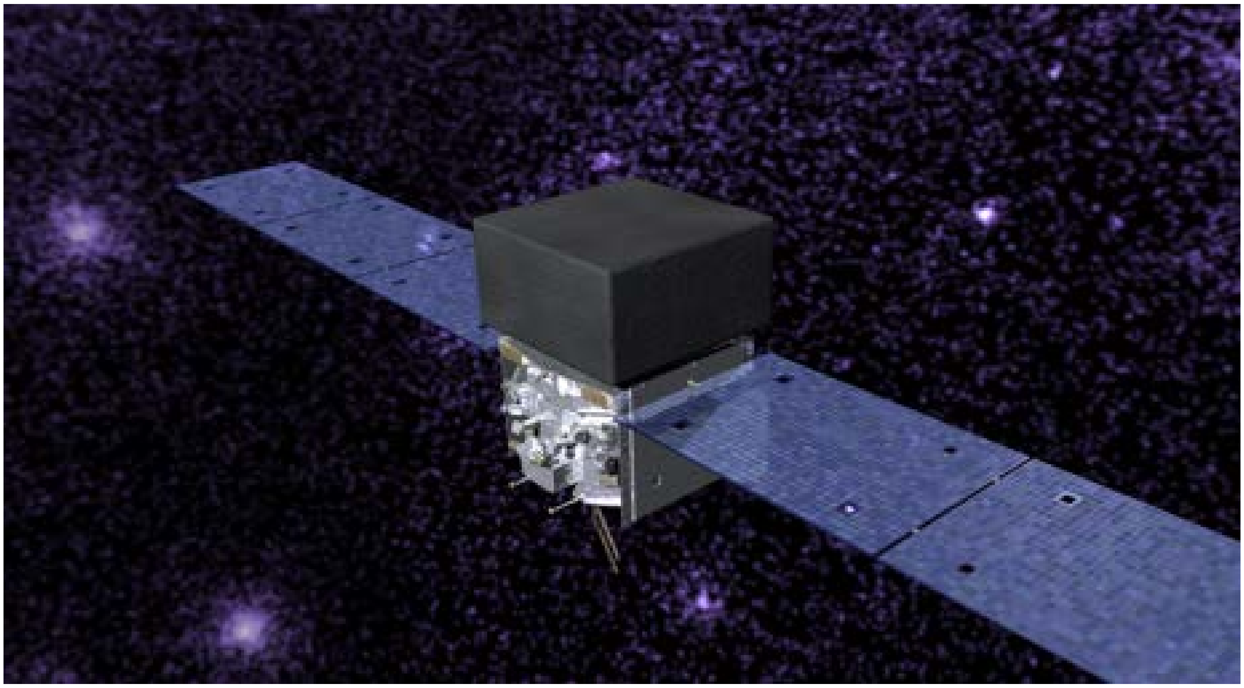

Figure a) Fermi Satellite

Figure b) Cherenkov telescope

Figure c) HESS detector

Figure 12: Several dark matter detection experiments, including Fermi Satellite, Cherenkov telescope, and HESS detector.

While dark matter is stable in many theoretical models, some theories propose that it could be unstable and eventually decay over cosmic timescales [31]. In the context of dark matter, decay refers to the transformation of a dark matter particle into other particles. Unlike annihilation (where two dark matter particles collide and produce other particles), decay involves only one dark matter particle. The decay process occurs spontaneously, and the resulting decay products carry away energy and momentum. The Large High Altitude Air Shower Observatory (LHAASO) in China is searching for gamma rays from the Milky Way and beyond, aiming to detect signs of heavy dark matter decay within our Galaxy [32]. The absence of such signs limits the decay rate of dark matter particles with masses in the PeV range. The team analyzed data from LHAASO's kilometer-square array, concluding that PeV-mass dark matter has a lifetime of at least a billion trillion years.

Another alternative for Dark Matter

Although Dark Matter is a well-established concept in contemporary cosmology, its fundamental nature remains unknown. As previously said, Dark Matter cannot be explained by any elementary particle found in the Standard Model. Such particles are still being sought after. There have been several suggestions for dark matter candidates, such as WIMPS, Anxion,... Through experiments like CRESST, the Axion Dark Matter Experiment, the Xenon Dark Matter Experiment, and the Dark Matter maps from the Dark Energy Survey, scientists are still looking for dark matter particles at the Large Hadron Collider. However, none of these experiments have yielded any results thus far. Naturally, one would then wonder: What if this is a problem with how we understand gravity? Furthermore, if we placed all of our hope in the DM paradigm, we would be ignoring a valuable lesson from the history of science: the confrontation of rather opposing paradigms has typically resulted in the accepted understanding of a phenomenon.

How MOND is theorized

Modified gravity is also known as “modified Newtonian dynamics” and is created for solving one of the biggest questions in cosmology, namely the problem of Dark Matter. Newtonian dynamics, based on the inverse square law of gravity successfully describes the motion of celestial bodies under the influence of visible matter [33]. However, when applied to galactic and cluster scales, it fails to account for the observed rotational velocities and gravitational lensing effects. To remove the discrepancy between the theory and the observed rotation curves, Milgrom, the father of MOND theory, proposed that at the edge of galaxies the gravitational force is weaker than in Newton gravity instead of invoking an invisible matter to explain stars in most galaxies are observed to move at similar speeds regardless of their distance from the center of the galaxy. This means that at extremely low accelerations (far from massive objects), the gravitational force behaves differently. More specifically, a criticall acceleration a_0 is introduced by MOND. It is stated that if acceleration were to exceed the critical threshold, gravity would be inversely proportional to the square of the radius according to Newton’s equations; if at a smaller acceleration, the gravity may fall off at one over radius instead of one over radius squared. Put another way, MOND predicts Newtonian behavior for galaxies, whose accelerations are usually bigger than a_0. MOND predicts departures from Newtonian gravity in the outer regions of galaxies [33].

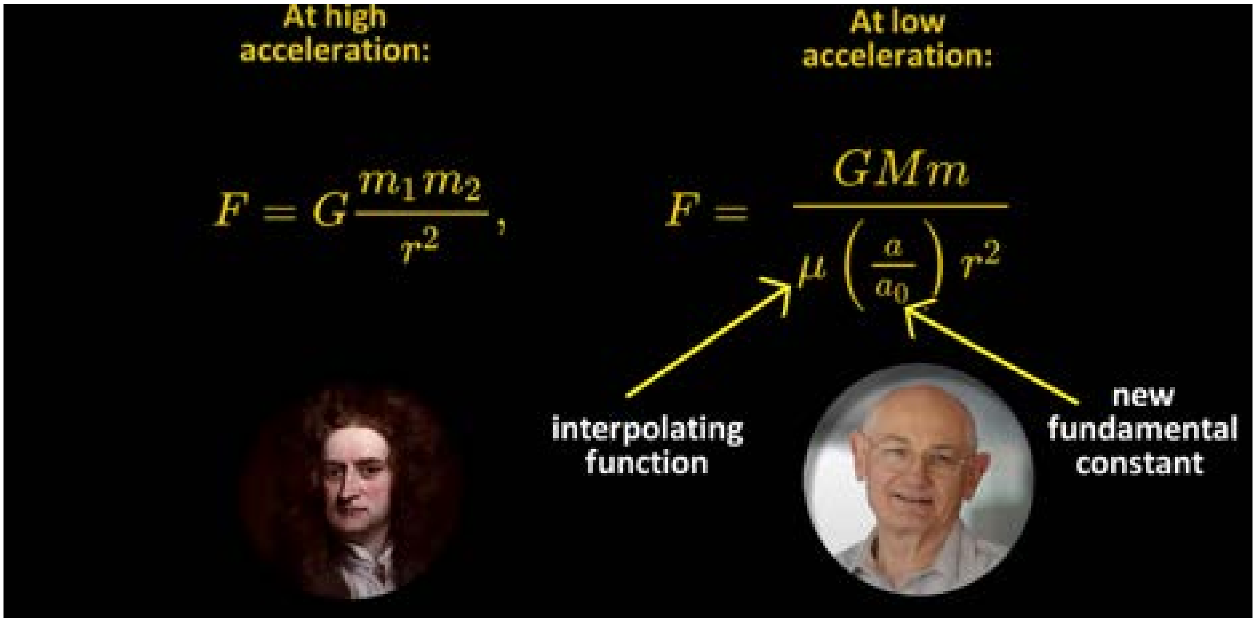

Figure 13 shows the comparison of gravitational force at different regions with different acceleration.

What MOND cannot explain

But why don't we just accept MOND as a new scientific theory and do away with dark matter as a particle entirely, given that we have not found any evidence of it in decades of searching? In science, very few things are flawless, and the MOND theory will inevitably encounter difficulties.

MOND is able to explain the motion of stars within galaxies, but not the motion of galaxies within clusters. This implies that MOND is unable to explain the bullet cluster, which points to the presence of dark matter. Gravitational lensing indicates that there must be invisible matter in the blue regions of bullet clusters [34].

Another problem for MOND is creating large-scale structures of the universe. This has been achieved by dark matter models when it comes to explaining how the cosmic web forms, but in order to explain those same formations without any other mechanisms being brought into play, MOND would need a lot more work done on it. As mentioned before, galaxies, galaxy clusters, and the cosmic web itself are formed through the gravitational collapse of initially small density fluctuations in the early universe. According to general relativity theory as well as dark matter’s postulated properties like non-interaction with light waves or other particles that interact electromagnetically while also remaining invisible altogether, this form still lacks explanatory power without considering modification theories such as adding new fields or combining them together within the framework of the MOND approach, which cannot produce this kind of structure because they do not predict hierarchical growths. Therefore, if there are no additional steps taken into account during these events, then the predictions made by modified Newtonian dynamics will not be able to match observed features associated with creation processes related to matter distribution over large volumes, known as the cosmic webbing phenomenon.

How MOND affects our understanding of classical physics and the whole universe

MOND offers a different explanation for the observed gravitational behavior, suggesting that modifications to Newtonian dynamics can account for the discrepancies without the need for dark matter. If MOND is empirically supported and widely accepted, it would require a significant shift in our understanding of the nature of gravitational interactions, understanding of the formation and evolution of galaxies, galaxy clusters, and the large-scale structure of the universe.

Scientists would need to explore the precise mechanisms and underlying principles that govern MOND, examining how its modified laws of gravity can reproduce the observed behavior without incorporating invisible matter. Additionally, the compatibility of MOND with other established theories, such as general relativity, would need to be thoroughly examined. Researchers could explore potential unification or modifications to existing theories that can incorporate MOND and provide a more comprehensive framework for understanding gravitational phenomena.

Conclusion

What we currently know about dark matter is both fascinating and perplexing. It influences the universe's structure, exerts gravitational pull, and is essential to the development of galaxies. Its makeup and how it interacts with ordinary matter are yet unknown, though. We get closer to discovering the mysteries of dark matter and learning more about our cosmos with every new finding. However, it is still unclear exactly what dark matter is and how it interacts, which motivates scientists to keep looking for solutions and piques their curiosity in the uncharted. To continue in the journey of finding the answer to this puzzle, scientists are still developing both experimentally and theoretically. Lately, besides WIMPs only left-handed neutrinos have been observed, but a hypothesis suggests right-handed neutrinos interacting only gravitationally, possibly as dark matter particles. And a bunch of other updated recent advances for both dark matter particles and non-dark matter particles, such as the possibility of dark matter's existence in primordial black holes. Aside from evidence bolstering the Dark Matter theory, there are an increasing number of alternative theories emerging to disprove Dark Matter, suggesting there is no room for Dark Matter.

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