What is dark matter and why is it important?

Abstract

Dark matter was required for the formation of galaxies and stars. We can also see how abnormal galaxy rotational velocity , gravitational lensing and most importantly the CMBR provides resounding evidence that there must be dark matter. I will explore some popular and less popular dark matter candidates and how we are trying to detect them through both direct and indirect detection. Finally, there are possible alternatives to dark matter one of which is a modification of gravity, specifically Modified Newtonian Dynamics which I will discuss.

Introduction

Ever since Galileo looked into the sky and revealed new planets and billions of stars, it was evident that there is so much more out there beyond what we can see in the night sky. And still, we point and gaze at new findings and shrink back from the wonderful structures to behold. But what if there was even more to it? Masses more to see that cannot been seen. Like Galileo admiring the craters of the moon, details that were always there but we are only just finding out.

You, your dog, the trees, the entire planet. We're all made of the same stuff, or if you want to be more scientific- matter. Matter, that is what makes up everything we can see, only makes up roughly 5% of the universe. About 27% is made of dark matter which is little understood, and the remaining 68% is dark energy which we are even further in the dark about.

Why do we need Dark Matter?

Maps formed of the early universe show that there were regions in the universe that were hotter and denser than others.

Figure A

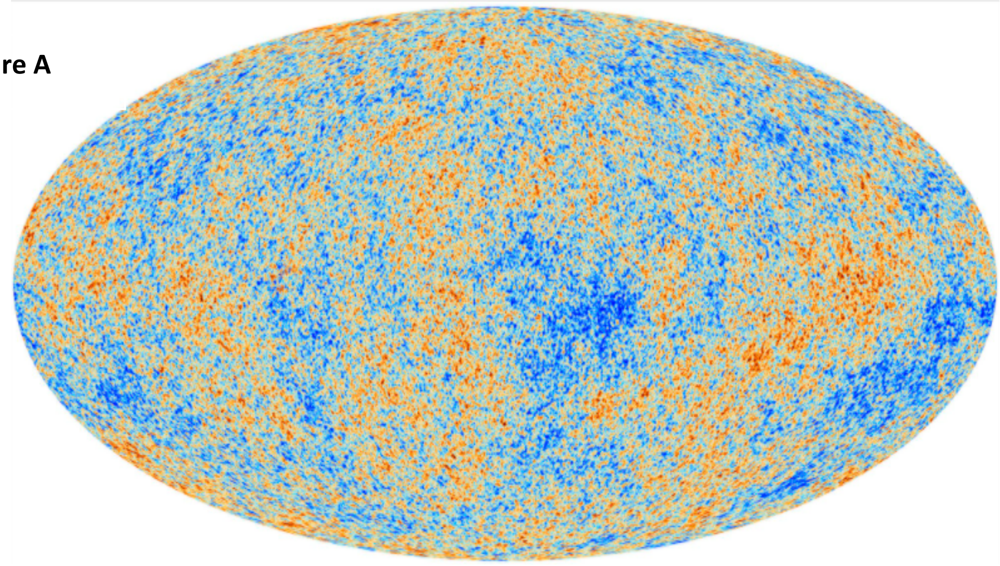


Image taken from the Planck satellite https://phys.org/news/2013-03-planck-reveals-universe.html

Forming these maps were possible due to the cosmic microwave background radiation (CMBR) which is the heat left over from the big bang. The CMBR has a general temperature of 2.73 Kelvin, but at the end of the last century, an important discovery was made with the COBE satellite. The temperature of the CMBR is not uniform, rather there are minute fluctuations in the temperature (represented by the orange and blue patches in figure A).

The early universe was very hot and dense. Too hot for particles to combine and form atoms. As soon as an electron would try to orbit around a proton , a photon of light would come and smash it apart as it had extremely high energy. But the universe was expanding, stretching out the

wavelength of the radiation, cooling it down. There would have been an epoch when most photons of light would no longer have had enough energy to break the electron away from the proton. At this point the radiation decoupled (separated) from the particles which is the formation of the CMBR.

What is key, is that there were fluctuations which, if theories are correct ,come from tiny irregularities known as quantum fluctuations in the field responsible for the exponential expansion of the universe and imprinted itself onto the CMBR. This occurred fractions of a second after the big bang called and is called inflation. The patches of higher temperature and density would have a greater interaction with gravity, pulling more mass towards those regions. If the universe were smooth, there would be no preferential path, no ripples for atoms to move in to drive them to move at all to begin forming anything. These hot and cold spots are imprints of what the early universe was like, and what we learn from that is that there must have been something else other than the normal matter right from the start. Without dark matter, the patches wouldn't have become massive enough to begin forming stars, and once they form the dark matter is needed to keep galaxies anchored together [1][20].

Abnormal galaxy rotation speeds:

Figure B

André van der Hoeven https://www.space.com/21854-andromeda-galaxy-m31-photos-gallery.html

In the 17th century, Johannes Kepler realized that the farther away a galaxy is from the sun the slower it orbits, and Newton calculated the strength of the sun's gravity and so the suns mass could be calculated. This can be applied to galaxies, as the velocity at which they rotate can be measured by their doppler shift, and so you can calculate the mass of the entire galaxy. When looking at galaxies astronomers Fritz Zwicky, and later also Vera Rubin ,who are both accredited for their data providing important evidence igniting the search for Dark matter, realized something strange. What they would have expected to see is that the farther to the edge of the galaxy, the slower the galaxy would be moving. However, what they observed was that farther out from the centre the gas clouds were moving much faster than expected , the rate was approximately constant throughout. This meant the galaxy felt a constant gravitational force throughout. Images of the galaxy (see figure B) clearly show a decrease in density of mass further out from the centre, there didn't appear to be enough mass to account for the rate of rotation. The explanation for this was that there must be a halo of this dark matter, an extra source of gravity, with a large part of it being around the edges of the galaxy that we are unable to detect allowing for this even spread of mass and gravity throughout the galaxy [2][3].

Gravitational lensing and galaxy clusters:

Einstein's theory of general relativity regards space as malleable, sort of like a fabric, with all of mass/energy embedded within it and gravity as a property of space.

Figure C

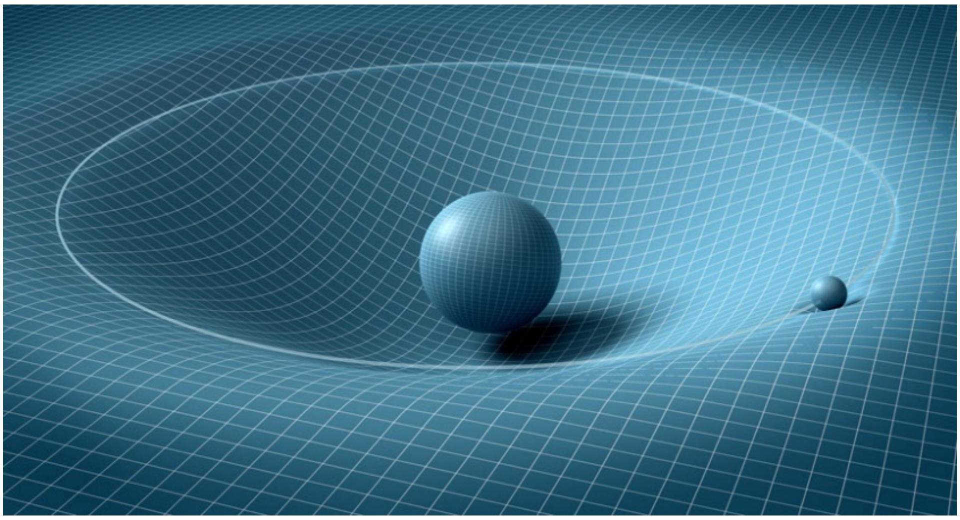


Image from: https://www.sciencenews.org/article/key-einstein-principle-survives-quantum-test

Objects in space such as planets have a warping effect on space as shown in figure C (which demonstrates an orbiting object). A more massive object bends space more. The distortion of space warps the path of passing objects and this is also true for light, so it follows that the more massive an object, the more it would warp the path of light. This is called gravitational lensing as it is analogous to a lens bending the path of light which has proven very useful for astronomers to map out where dark matter should be in the universe[2][22].

The Bullet cluster

Galaxy clusters make useful gravitational lenses-they have a lot of mass in a relatively small space. A galaxy in the background of the cluster to us would emit light that gets bent on its way to us and the image of the galaxy gets smeared out and distorted by the time we can see it. According to Einstein's equations, the amount of this bending, and how it is bent is dependent on the mass distribution of the cluster. By measuring the amount of gravity that object has, you can measure the mass distribution of the cluster all by the distortion of the objects behind it. When measuring the mass of galaxies, it was found that the actual mass was much larger by orders of magnitude to the mass that was observed, especially towards the edges of the galaxy like a halo. Another clue that there must be something else out there accounting for this extra mass [2][30].

Gravitational lensing is the method astronomers used on a group of galaxy clusters called the bullet cluster about 3.8 billion light years away[24]. The bullet cluster is actually a collision of two clusters. When galaxies collide, they tend to just pass through each other, but in clusters there are vast amounts of gas between the galaxies which do collide with each other and get so hot they emit x-rays. We can use optical light images showing the clusters next to each other after they've passed through each other, and because the gas in the clusters couldn't pass through each other they remain mostly between the galaxies as the gases slow down much more than the stars as they feel an electromagnetic drag force. Astronomers used the Chandra X-Ray observatory to map out where the hot gas was which as expected, was mostly between the galaxies shown in figure D as the two pink clouds[23].

Figure D

Image from: https://apod.nasa.gov/apod/image/0608/bulletcluster_comp_f2048.jpg

This gas makes up most of the baryonic matter of the two clusters, but this and the optical galaxies does not account for much of the mass. The surrounding gas shown in blue is the distribution of dark matter in the cluster. If the hot gas were the most massive component in the clusters, it is thought that this effect of the separate clouds of the baryonic gas and surrounding mass (dark matter) would not be observed. It also demonstrates that the dark matter does not interact with the gas clouds made of 'normal' matter or perhaps even itself. These observations have also been made in many other clusters which provides more indirect evidence for dark matter [24][25].

What is dark matter?

The most cogent idea is that dark matter (DM) is a particle yet to be unveiled . It must interact with the gravitational force in order to serve its purpose as DM. However, it interacts very weakly with 'ordinary' matter and doesn't appear to emit or absorb any electromagnetic radiation making it exceedingly difficult to detect.

One categorization for the candidates of DM is baryonic matter, that is ordinary atomic matter in contrast to non-baryonic matter.

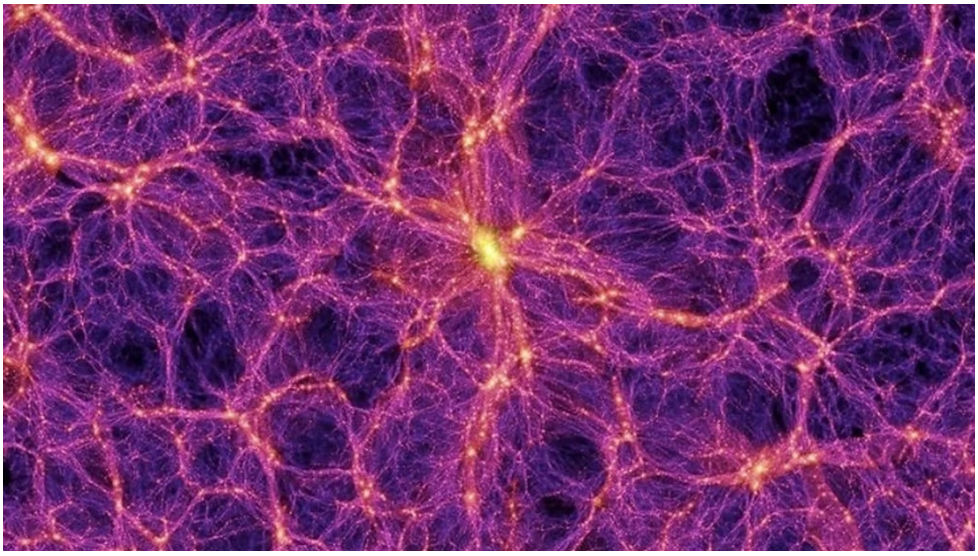
MACHOs

There is a class of astronomical bodies, which would be baryonic matter, that could be the dark matter and escape detection. These are known as massive compact halo objects (MACHOs) which are structures we already know exist and are massive so will exert a large amount of gravity yet are too dim to see. Some proposed MACHOs have been small brown dwarf stars with masses below 0.08Mo [28], black holes and neutron stars, and could be observed by gravitational lensing. MACHOs were once a top contender but there are many flaws to this idea leaving MACHOs as a top candidate to history (at least in the question of what makes up the primary component of DM). The main reason for this is that ordinary matter will give off or absorb some form of radiation. If there was enough of this MACHO matter to account for DM, it is very unlikely that today's detectors wouldn't have detected anything from it. Furthermore, we have the evidence from the CMBR which tells us to a very precise accuracy of within 1% [30] how much baryonic matter there is and how much total mass there is, there is much more total mass than accounted for by baryonic matter and so there must be something else [26][27][28] .

Another classification is hot or cold dark matter, this depends on the size of the particles. The size of the particles determines their velocity, and this then determines their thermodynamic properties When testing models for dark matter, a key tool is computer simulations. Scientists can use the information from the CMBR to trace back to the early universe using the quantum fluctuations from the inflation which were like tiny seeds that sparked the formation of galaxies and clusters. They will then plug into the computer an assumption , a candidate for dark matter, a rule for the universe to obey .These computers then compute for months to produce a simulated universe based on the data you fed it. When the rules and assumptions are correct, this universe that comes out will look like the one we live in [30][31].

A simulation that appears to accurately predict the formation of our universe shows the importance of dark matter as a skeleton for the large-scale structure of the universe. In the early universe when DM dominated, it gravitationally attracted to itself forming filament like structures like a massive web. Baryonic matter was attracted to larger concentrations of dark matter and clumped together into galaxies. Each yellow dot is an entire galaxy, and the purple dark matter [41].

Figure E



https://bigthink.com/surprising-science/cosmic-web?rebelltitem=1#rebelltitem1

Neutrinos

One hot dark matter candidate has been neutrinos. We already know they exist, that they interact very little with matter and that they are also abundant. It was proposed that if each of these neutrinos had a little mass, then trillions of them could account for DM. However, following experimentation the upper limit for the mass of the neutrino has been determined to be too small to account for DM. The problem with neutrinos, and other hot dark matter candidates, is that they don't match with the structure formation we see using the computer simulations for the evolution of the universe. They move extremely fast so escape the initial density fluctuations in smaller concentrations. Their mass makes up these fluctuations in the first place, so if only the larger ones can survive then only large structures form at the beginning to the expanse of galaxies, even clusters which later break into smaller structures. This does not at all concur with the models we have predicted in which smaller structures merge to larger ones [6][32].

So that leaves us with the generally accepted model being Cold, or at most warm and non-baryonic dark matter as the primary component.

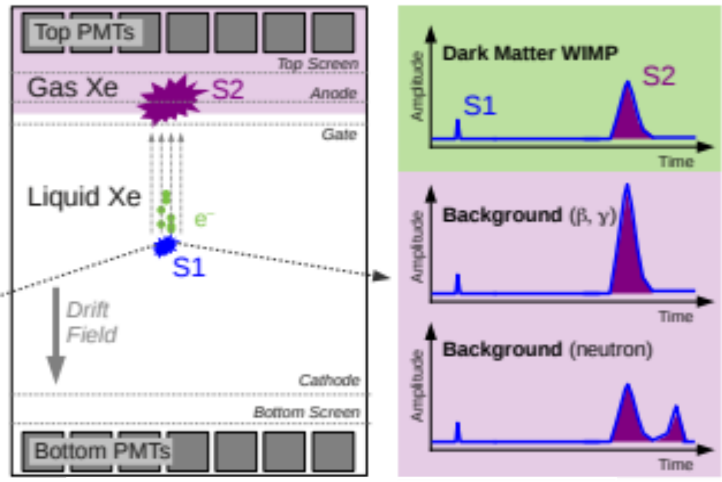
WIMPs

Weakly interacting massive particles (WIMPs) come from an already existing theory of supersymmetry which promises a solution for a unification of the fundamental forces. It extends the standard model as it predicts a partner particle for each particle in the standard model [16][28].In many theories the lightest supersymmetric particle is predicted to be stable and electrically neutral. They will have a very large mass but only interact with regular matter through the elusive weak force (as well as gravity). WIMPs were put into the spotlight following what was dubbed the "WIMP miracle" which describes the surprising correspondence between the dark matter abundance experimentally observed and the value expected for it under the typical mass and interaction strength which popularized them as a cold dark matter candidate.

Scientists can try to detect WIMPs through both direct and indirect detection. Indirect detection refers to the observation of products of decay or annihilation (typically gamma rays) from WIMPs away from earth where DM is thought to accumulate most, such as in galaxy clusters. The dwarf spheroidal satellite galaxies of the Milky Way, for example, are of the most DM-dominated dominated objects known [11] . Direct detection would be the observation of the effects of a WIMP-nucleus collision when the DM passes through a detector [10]. One issue in direct detection is the "neutrino floor" which determines when the detectors are sensitive to the neutrino background which would make it more difficult to detect the WIMPs as the WIMP and neutrino interactions look very similar. Axions, which will be discussed next, appear differently in a detector so the "neutrino floor" isn't an issue [12].

XENON 1T (the detector is depicted in figure F) is the most sensitive DM detector yet. It contains 3.5 Tons of, believe it or not, pure xenon and is located deep underground to prevent cosmic ray interference. At low WIMP masses, the sensitivity nears this "neutrino floor"[4][5] .

Figure F



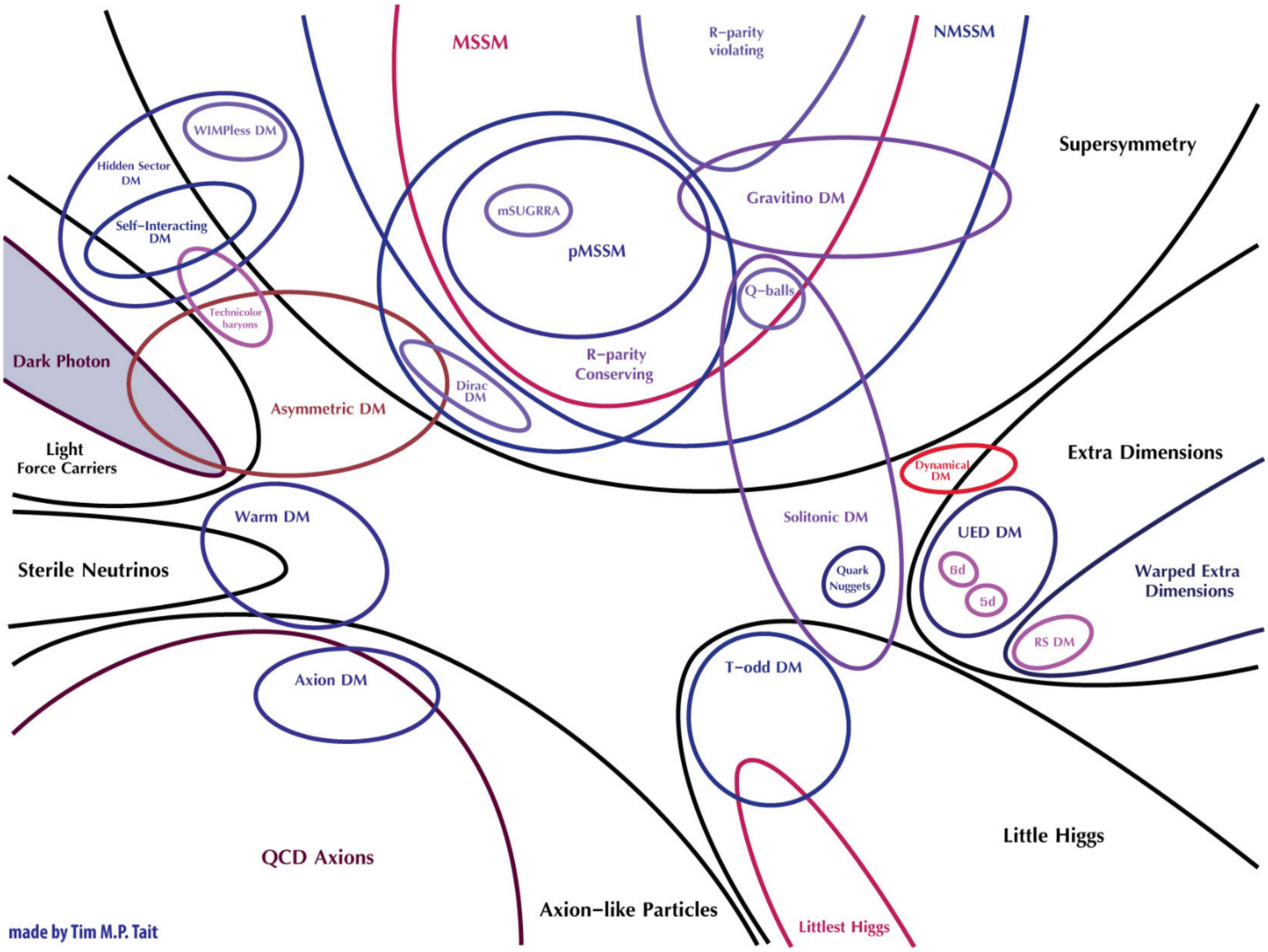
https://arxiv.org/pdf/1708.07051.pdf

When dark matter particles pass through the detector (figure F), eventually a particle will interact with a xenon atom and it will recoil, producing a flash of light. The light is detected at the photomultipliers (PMTs). It will also produce a free electron which accelerates up to the top of the detector and another flash is produced. Therefore, there should be two flashes at set time intervals and proportion of brightness signifying a WIMP interaction (and not a background particle) [4].

There was an excess of events (more detections than could already be explained and expected from background particles) reported in a 2020 paper on the XENON collaboration, (over 100 names on the paper) [43]. They could be due to background contamination by tiny amounts of tritium in the detector, neutrinos, or more optimistically an undiscovered particle which could be a dark matter particle. However, the experiment didn't detect enough flashes at the right energy levels to back up the existence of WIMPs, many possible varieties have been ruled out and due to the high sensitivity of the detector it is unlikely anything was missed out [5][13][14]. More worrisome for this beloved theory, is that with two runs at the large hadron collider (LHC), no detections for any supersymmetric particles have been found. Of course, this doesn't rule out WIMPs for sure for example, they could be heavier than first thought or the probability of producing the super-symmetric particles at LHC could be smaller than expected and there are some other models that could survive this [36][37].What could be a last attempt for detecting a WIMP is the DARWIN XENON project, which is an international collaboration of a generation of detectors including the XENON 1T. This projects at least another 10 years in the search for WIMPs. The reason it is most likely going to be the last generation of detectors is because it will reach the neutrino floor previously explained[15].

There is however no shortage of weird and wonderful ideas to be explored (figure G).

Figure G

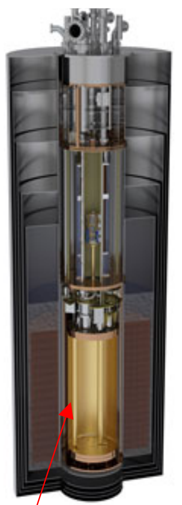


Non-WIMP candidates 10.1515/phys-2016-0034

Axions

There are other cold DM candidates , one of which are axions which could also potentially explain the excess of events in the XENON 1T experiments. Axions were postulated by the Perccei-Quinn theory which is a possible solution to a different problem in physics known as the strong C-P problem. That is that the strong force should violate CP symmetry, but experiment hasn't shown any signs of this. C-P symmetry means that a particle with both an inversed charge (its antiparticle) and parity should behave in exactly the same way in physical interactions. Parity is an inverting transformation, which for illustrative purposes can be thought of like a mirror image, it is the change in the signs in all three-dimensional coordinates [34][35].This comes under Quantum chromodynamics (QCD) which is the theory of the strong interaction between quarks and gluons, hence QCD axions (as shown in figure G). If these QCD axions exist in a specific range with low mass, they also stand as a compelling candidate for cold dark matter . The originally hypothesized axion which would have been of order 100 keV mass and had interactions large enough to enable the axion to have been produced and detected in conventional laboratory experiments. All experiments searching for this came back negative, and so that was the first upper bound limit placed on the axion mass. There have been more encouraging experiments from other models further narrowing the possible range for the mass of the axion. One paper mentions how stellar evolution (how stars change overtime) sets limits for the coupling (interactions) of the axions to radiation, electrons, and other particles "so the mass limits are only placed indirectly and often with large uncertainty. "[7][8][9]. A 2016 paper describing gamma ray data from neutron stars concluded a concurring upper limit mass of 7.9×10^{-2} eV with a 95% confidence level.[33]

Figure H [17]



ADMX searches for DM in the galactic halo. It is the only detector with the sensitivity levels predicted for dark matter searching for axions. It uses what's called a radiofrequency cavity which confines electromagnetic fields in the microwave region of the spectrum. The microwaves bounce between the walls of the cavity which at a certain resonant frequency forms a standing wave in the cavity. This is like a filter only allowing microwaves at a particular frequency to pass. DM axions could weakly couple to the magnetic field in the cavity to produce photons which are detectable and would have the same frequency as the cavity is tuned to, increasing the number of photons produced. ADMX has eliminated possible masses on the micro-eV order. The detector in the ADMX is shown in figure H

ADMX and similar methods continues to narrow the mass range down, whilst we haven't found evidence that axions exist, this process of narrowing down a range for a particle so unwilling to interact with matter is exceptionally important for LHC experiments to know exactly where to look. [17][18][19]

Other ideas

As promised, there are many other intriguing ideas. One of which is the Kaluza-Klein particle which comes from Kaluza-Klein theory that opens a fifth dimension, (the fourth being time) and a fifth that curls up in space. This theory predicts the existence of a potential DM particle which would be able to interact by both electromagnetism and gravity yet is curled up into a dimension invisible to us. To look for these particles, we should be able to measure the particles it decays into such as neutrinos and photons which the LHC is yet to detect. This particle is a WIMP, but it comes under the universal extra dimensions (UED) model rather than a supersymmetric one (SUSY)[27].

Detecting Dark Matter

As previously mentioned, there are direct and indirect methods of searching for DM particles. Due to the nature of DM being very weakly reacting, if at all, with baryonic matter through anything other than gravity it is incredibly hard to detect. Dark matter would usually just pass straight through our detectors which use the electromagnetic spectrum, X-rays, gamma rays which Dark Matter does not emit. This is why detection methods such as in the ADMX and XENON experiment wait for or try to provoke rare instances in which the potential DM particles may produce a photon or gamma ray. For example, it is probably that dark matter is its own antiparticle. Therefore, in extreme conditions such as the centre of the Milky Way, densities are so big the DM particles could collide and annihilate each other producing gamma rays and antimatter which could be detected. Then there is the option to 'make' the particles at the LHC by colliding particles together and looking through the data for 'dark matter signatures', for example if the total momentum after a collision isn't zero, it could have been carried away by an undetected particle (Momentum before the collision would be zero and so must end with zero by laws of conservation).

The indirect/ direct detection methods and the LHC go hand in hand. If evidence for the existence of a particle were to arise at the LHC which is thought to be a candidate for DM, we may have found it exists, but the direct/indirect detection would be needed to confirm that it is a constituent of DM. On the other hand, if a DM particle were detected by indirect/direct detection, the LHC could unveil more information about the particle's interactions. A big hurdle when searching for dark matter, aside from its reluctancy to interact with baryonic matter, is that whilst we know how much DM there should be to match astronomical observations, we do not know the masses of its individual components. There is such a large pool of possible particles and their associated mass ranges for the DM particle, it is bound to take a very long time to narrow down the possibilities [30][38].

Alternatives?

The evidence we have for dark matter by observation is indisputable. As well as this, the CMBR tells us to a very high precision how much baryonic matter there is, and how much total mass there is, and there is a large gap between the two. However, we haven't actually detected any dark matter.

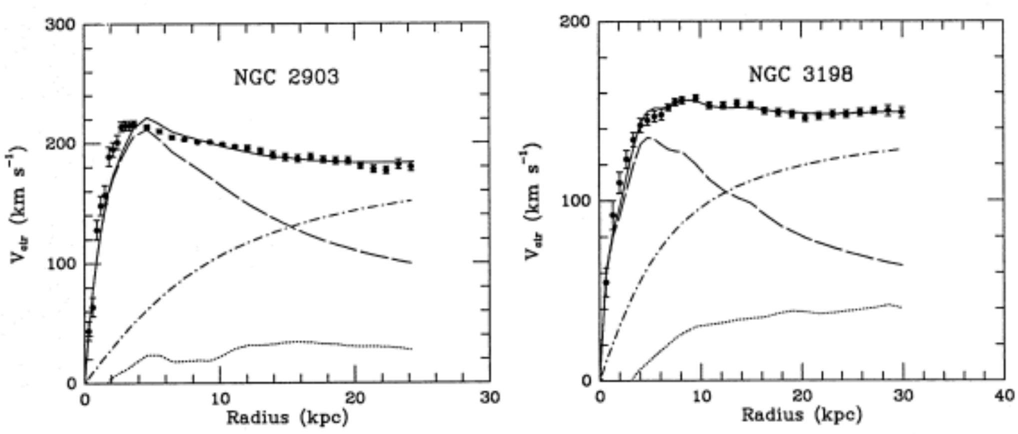
Much of the evidence we have for DM assumes our understanding of gravity is correct. There are alternate explanations for how the universe could have formed without DM in theories of modified gravity. Newtonian gravity and Einstein's general relativity are strongly confirmed by observation, but we still can't dismiss the idea that our understanding may be slightly wrong on a fundamental level. It is also important to note that we now have access to much more distant astronomical phenomena to be considered than at the time of Newton and even Einstein. The most popular hypothesis for those not so keen on exotic particles is modified Newtonian dynamics (MoND) hypothesized by Mordechai Milgrom.

What has been observed is that at the centre of galaxies rotation speed is as expected, we don't need DM to explain this. It is only the outer parts, the 'halo' surrounding the galaxy where gravity can't explain the faster than expected rotation velocity. There appears to be a critical value outside a certain radius or acceleration after which Newton's laws of gravity do not seem to fit in. So, what MoND proposes is an extra term in Newton's equation, allowing it to account for these situations. One way of looking at MoND is that at large radii and smaller accelerations, the gravitational force would fall of inversely to radius rather than decaying more quickly by an inverse square law, $g=GM/r^2$ as per Newton's laws. It also offers modifications Newton's second law at low accelerations.

This all means that the seeming mass deficiency would be explained by different acceleration felt by the objects due to gravity behaving differently in these situations.

MoND appears to fit our observations of stars in our galaxy really well. Yet it doesn't explain the motion of galaxy clusters such as the aforementioned bullet cluster. Due to this, most advocates for MoND don't believe you can completely replace the idea of a DM particle as attempts to fix these inconsistencies have been as of yet unsuccessful. The advantage to combining both MoND and DM particles is that it expands the requirements for DM giving baryonic matter candidates a chance. However, the largest flaw in MoND or a MoND- baryonic matter collaboration, is that it doesn't account for the missing mass needed to make the universe as we see it.[39][40]

Figure I



K.Begeman, A.Broeils, R.Sanders, 1991,From the 'Monthly Notices of the Royal Astronomical Society'

https://academic.oup.com/mnras/article/249/3/523/1005565

Figure I shows the rotation curves of the individual components of sample galaxies. The solid black line shows how Milgrom's equations fit our measurement of galaxy rotation (the error bars), the dashed and dotted curves are stars and gas, and the dot-dash curve is the dark halo. The fitting parameters are the mass to light ratio, the halo core radius, and the circular velocity [42].

Conclusion

There is resounding evidence from observation and especially the CMBR that without a doubt there is something that doesn't add up. The mass can, in some places, be up to a factor of 100 more than what we observe. Without dark matter galaxies wouldn't have been able to form or stay intact. There would be no stars and no planets. the most certain thing we can say is that there is some unknown origin of gravity keeping galaxies and clusters together. However, we don't know what it is yet. Our best simulations show that dark matter is most likely in the form of a cold, non-baryonic, particle that is yet to be discovered, but until we actually expose the identity of what this particle could be, we must also consider other possibilities such as flaws in our understanding of gravity. Finding dark matter (or whatever else may be causing the observations) would be uncovering the way our universe evolved which would certainly be an exciting discovery.

And for some optional light relief…

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