Dark Matter Matters!

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Abstract

Reality points out that visible matter, which is everything that you see on earth and in space, accounts for only a tiny fraction of all the matter that exists in this universe. The rest is just Dark energy and Dark matter. Dark matter makes up about ~26% of the observable Universe. Here, we study various evidence showing the presence of this 'missing mass' , its composition, the possible candidates of dark matter, and its effects on Galaxies and clusters. The evidence of dark matter that we study include galaxy rotation curves, extended emission in X-ray observation of galaxy clusters and gravitational lensing. This report is based on the evidence of the existence of dark matter, Nature and Detection of Dark matter, some hypotheses such as WIMPs, SIMPs, Axions, MACHOs, Neutrinos, Sterile Neutrinos and Dark Photons. We also study its effects on Red Giants. The alternate theory that explains the missing mass problem, MOND, will be discussed in brief.

Keywords: Energy density, Stellar rotation, Cosmic Microwave Background (CMB), Scattering Cross Section, Matter budget, Galactic Halo, Bullet Cluster, Uncertainty Principle, Gamma Rays, Cosmic rays, Super Symmetry, WIMPs, gravitational lensing, Axions, Sterile Neutrinos, Kaluza Klein Theory.

1. Introduction

According to the data obtained from various astronomical observations, certain gravitational effects for instance, cannot be explained by Newtonian mechanics unless we assume the presence of another sort of matter that can neither be seen nor detected due to the fact that it does not interact with Electromagnetic waves. It is completely intangible and can only be detected via the gravitational pull it exerts. It remains one of the greatest mysteries in the universe, an invisible substance thought to make up five-sixths of all matter in the universe.

Research teams across the globe are striving to discover what exactly this mystery is. The first scientist to suggest the existence of this peculiarity was the Dutch astronomer Jacobus Kapteyn in 1922 using stellar velocities. The major research in the field of dark matter hit a milestone when Swiss astronomer Fritz Zwicky in the 1930's estimated the total mass of the Coma cluster and found that it is much larger than the visible mass. He referred to this unseen mass as "dunkle Materie" or "Dark Matter", henceforth referred to as 'DM'.

Another major observation made by many scientists was that the Energy density of this missing factor was inversely proportional to the cube of dimension factors. But as we know, only the volume of matter is proportional to the cube of its length dimension, and Matter density has dimensions of mass per cubic length. Thus, this missing factor should have the dimensions of mass. In the 1970's Vera Rubin in collaboration with W.K. Ford studied the rotation of the Andromeda galaxy and observed that the stars are rotating faster than expected. They studied many other spiral galaxies and reached the same conclusion that the mass of all those galaxies is larger than the visible mass. In the 1980s many observational evidence such as gravitational lensing, patterns of anisotropy in the cosmic microwave background, and the temperature distribution of hot gasses in galaxies & clusters have further proved DM.

DM occupies nearly 84% of the Universe's matter budget. While there is no shortage to the predictions of DM particles, there is no certain explanation as to how and when DM formation began. From the various observations of galaxies made during the late 19th and the early 20th century, the idea of DM's presence is highly favoured. It's effects are seen at the galactic levels and also probably on the Red Giants, such as luminosity of the star, its temperature, and the lifetime of the star. The effects of DM, however, belong to a time scale where the Universe was at least a few Billion years old. The predictions to how DM behaved during the Universe's infant stages can be done by visualising the Cosmic Microwave Background. The scientific consensus right now is that DM is composed of a new type of particle, some models suggest these particles could give off gamma rays when they decay or when they collide with and annihilate each other. The gamma rays scientists detect in the universe could therefore reveal whether DM particles actually exist, and what their properties might be, such as mass and the cross-sections, or the way in which they interact with other particles. All the evidence for the existence of DM and constraints on its nature come from Astronomical Observations.

There is one other theory that tries to explain the peculiarity observed in the galactic rotational curves by modifying the Newtonian Dynamics and hence named MOND. But, does this theory hold up against the tests thrown at it at other cosmological levels?

2.Evidences of Dark Matter

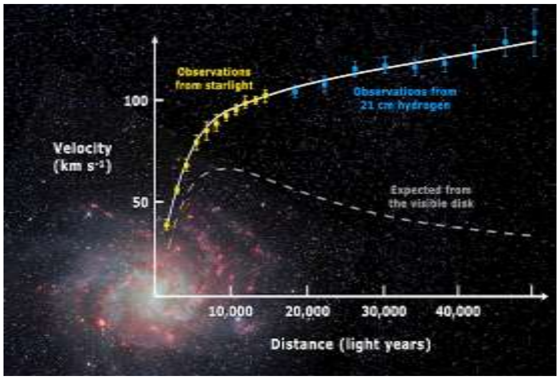
Determining the identity of DM has largely shifted to the fields of astroparticles. DM does not emit, absorb, or reflect light. Its presence is only known through its gravitational pull-on visible matter in space. The idea of DM is very well explained by other observations too. The various evidence for the existence of dark matter includes Galaxy clusters, Galactic Rotation Curves, Cosmic Microwave Background, Bullet Clusters. Galaxy clusters are the most massive structures in the universe composed of individual galaxies and are the largest repositories of DM.

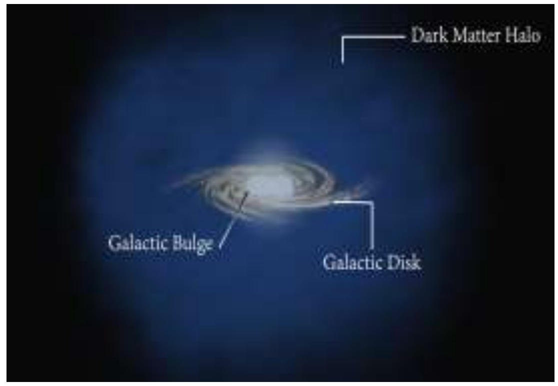
2.1 Galaxy rotation curves

One of the strong evidences of DM is that most galaxies have rotation curves that show solid body rotation in the very center, followed by a slowly rising or constant velocity rotation in the outer parts. Since all stars revolve around the centre of galaxy by Newton's laws we get orbital velocity to be:

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

where 'r' is the Radial distance from the centre. Since $v \propto r^{-1/2}$, the expected curve for the orbital velocity of stars to the radial distance from the centre of a galaxy keeping in mind the effect of gravitation produced only by stars should increase at first because of increasing in mass as the number of stars increases and after attaining the peak velocity should decrease because the number of stars decreases along the edge of the galaxy. Surprisingly that was not observed. Rather, the orbital velocity remained almost a constant after attaining the peak value. So there has to be some other unseen mass that is driving the orbital velocity of stars to a great speed. This mass is said to be DM. So then the mass of the galaxy increases as the radial distance increases.





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We substitute M = M_o r for large values of 'r'. Then, the orbital velocity becomes:

$$v = \sqrt{\frac{GM_0 r}{r}}$$

Or

$$v = \sqrt{GM}$$

Hence orbital velocity becomes a constant for very large values of ‘r’. This increase in mass is nothing but due the presence of DM. The calculations revealed that the mass of DM present is 5 times the amount of the normal matter.

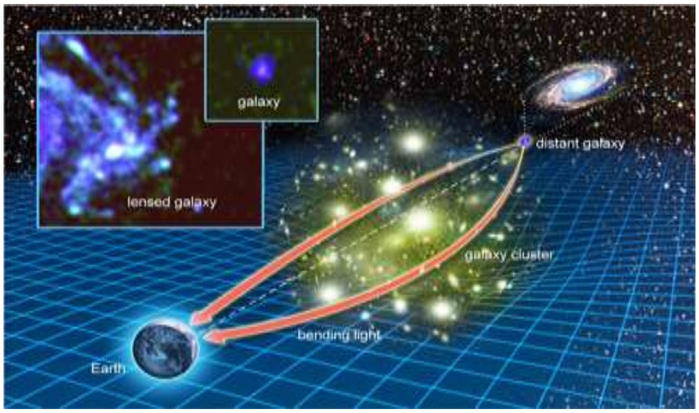
2.2 Extended Emission in X-ray observation of Galaxy clusters:

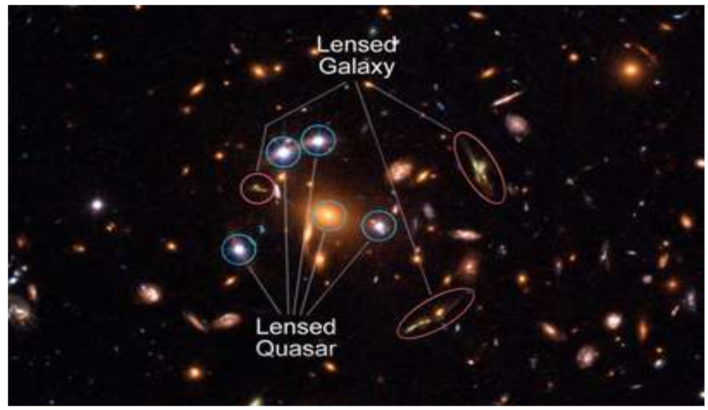
This observation indicates that there is presence of hot gas distributed throughout clusters obeying $kT=\frac{1}{2}mv^2$ where v≈ 1000m/s and T≈ 60000000K. So this, in accordance to black body equation, the wavelength of light emitted is in X-ray. From this information, luminosity can be measured which depends on density, Temperature, and volume of the cluster. So the result which was obtained is that the mass of stars alone is not enough to hold this hot gas, so there is presence of additional matter which is DM that provides enough gravitational force of attraction.

Example: Chandra X-ray observatory calculated distribution of DM on ABELL 2029 galaxy cluster which showed the presence of 25% DM and & 70% Dark Energy.

2.3 Gravitational Lensing:

According to Einstein's General theory of Relativity, Gravity is caused due to the strain on the Energy-Momentum tensor which makes the matter to curve the fabric of spacetime. So the path of light which follows space gets bent. So when the light emitted by the source object passes near massive objects, the gravitational pull from these objects can distort or curve the spacetime around it thus bending the path of light. This bending of light makes the source object look bigger due to the magnifying effect produced (like an optical lens). This is called gravitational lensing.





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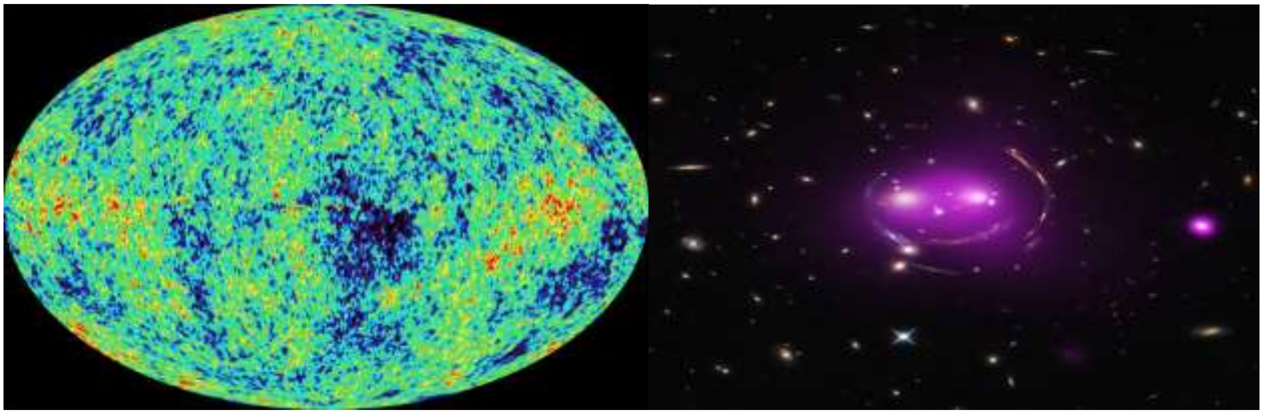
The most useful hint that scientists got was that in some parts of the universe this gravitational lensing effect is produced even when there is no presence of normal matter. It is as if the light from an object bends on its own, but it is caused due to the presence of DM in that region. So, by observing this effect in various parts of the universe scientists mapped the regions in the universe with high density of DM which is shown below in blue shade.

Gravitational lensing is most easily observable around a dense concentration of mass like the core of a galaxy or a cluster of galaxies. In the "strong lensing" regime, nearby space-time is so warped that light can travel along multiple paths around the lens, and still be deflected back towards the observer. If a distant source is directly behind a circular lens, the light can travel around any side of it, and appears as an "Einstein ring." The Einstein radius or size of this ring is proportional to the square root of the projected mass inside it. If the background source is slightly offset, or the lens has a complex shape, the source can still appear in multiple locations, viewed from very slightly different angles.



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In a recent study on 10 september 2020 by the Hubble Space Telescope, Astronomers have discovered that there may be a missing ingredient in our cosmic recipe of how DM behaves. Researchers found that small-scale concentrations of DM in clusters produce gravitational lensing effects that are 10 times stronger than expected. The researchers believe that the embedded lenses are produced by the gravity of dense concentrations of dark matter associated with individual cluster galaxies. DM's distribution in the inner regions of individual galaxies is known to enhance the cluster's overall lensing effect.

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2.4 Primordial nucleosynthesis

When the universe was a few hundred seconds old, at a temperature of ten billion degrees, deuterium became stable: $p+n \rightarrow D+\gamma$. Once deuterium forms, helium and lithium form as well. The formation of heavier elements such as C, N, and O must wait a billion years until stars form, with densities high enough for triple interactions of three helium atoms into a single carbon atom. The predictions from the Big Bang are 25% Helium-4, 10−5deuterium, and 10−10Li-7 abundance by mass. These predictions exactly match the data as long as atoms are only 5% of the total constituents of the universe.

3. Nature of Dark Matter particles

- Mass limitations for DM particles can be calculated by using Newton's law on Gravitational Potential, (where M = Total mass of all stars in the galaxy, m = mass of DM particle and r is radial distance between DM particle and center).
  Using Uncertainty principle,

  $$r = \frac{h}{4\pi^2 GMm^2}$$

  Since the value of ‘r’ should be such that the particle remains confined to the galaxy, the mass range of DM can be limited to a range of 10^{-31} GeV to 10^{50} GeV.

- The calculation of collision between clusters which cause bullet formation showed that the interaction between DM particles should be less than 35kpc/h for a typical scattering cross section of 1.75×10^{-25} cm².
- Dark matter cannot consist of baryons. The first evidence supporting this claim is that if baryons made up all the DM, the CMB and cosmic web of structure would look radically different. Secondly, the abundance of light elements created during big-bang nucleosynthesis depend strongly on the baryon density of the Universe. From CMB observations, abundances of deuterium and He-4 provide similar constraints on the baryon density in the Universe. From these points, the popular class of baryonic DM candidate, Massive Compact Halo Object (MACHOs) (e.g., brown dwarfs, stellar remnants) is cosmologically insignificant. DM cannot consist of light (sub-keV-mass) particles unless they were created via a phase transition in the early Universe (like Quantum ChromoDynamics axions). This is because light particles were relativistic at early times and thus fly out of small-scale density perturbations. Some DM hypotheses are the QCD axions, axion like particles, fuzzy cold DM in the group of light bosons and fermions in the standard model like sterile neutrinos. On the weak side, there is Supersymmetry, extra dimensions, little Higgs, Effective Field Theory and simplified models. The other particles are Weakly Interacting Massive Particles (WIMPs), Superfluid Vacuum Theory and Microscopic DM. And the Modified Gravity categorise the Modified Newtonian Mechanics(MOND), Tensor Vector Scalar Gravity (TeVeS), Entropic Gravity, Quantized Inertia.

4. Classification of Dark Matter

4.1 Cold Dark Matter (CDM)

● Cold DM particles move at very slow speeds. Hence, can be theorised by non relativistic equations.
● 90% of the DM is cold because only this has the capacity to form lumps and can hold the galaxy together.
● Proposed candidates are WIMPs, Supersymmetric particles, superstrings, Kaluza Klein(KK) particles, etc.

4.2 Hot Dark Matter (HDM)

● Hot DM particles move at very high speeds close to the speed of light hence can be theorised only by relativistic equations.
● HDM contributes very less percentage to dark matter. Because HDM particles can't form clusters on the Galaxy because of high energy.
● Proposed candidates are Neutrinos.

4.3 Warm Dark Matter (WDM)

● Properties of WDM particles are intermediate to CDM and HDM.
● Proposed candidates are Sterile Neutrinos and Gravitinos.
● Mass of these Particles are higher than that of CDM and lower than HDM.

5. Detection of Dark Matter particles

The identity of DM is a question of central importance in both astrophysics and particle physics. In the past, the leading particle candidates were cold and collision less, and typically predicted missing energy signals in particle colliders. However, recent progress has greatly expanded the list of well-motivated candidates such as Weakly Interacting Massive Particles (WIMPs), Axions, Strongly Interacting Massive Particles (SIMPs), light gravitinos, hidden dark matter, sterile neutrinos and the possible signatures of DM. Like WIMPs and Massive Astrophysical Compact Halo Objects (MACHOs), theoretically, SIMPs are also produced in large quantities and cooled to the average cosmic temperature. But unlike WIMPs, SIMPs are theorized to interact strongly with themselves via gravity but very weakly with normal matter. Japanese physicist, Professor Hitoshi Murayama, proposed that there is a possibility that SIMP is a new combination of quarks, which are the fundamental components of particles like protons and neutrons, called baryons. Whereas, protons and neutrons are composed of three quarks, a SIMPs would be more like a pion containing only two: a quark and an antiquark. To identify the nature of DM particles, direct DM searches are promising techniques. The main techniques and R&D projects that will allow to build the so-called ultimate WIMP detectors, capable of probing spin-independent interactions down to the unimaginably low cross section of 10^{-48} cm^2, before the irreducible neutrino background takes over. If a discovery is within the reach of a near-future DM experiment, these detectors will be able to constrain WIMPs properties such as its mass, scattering cross section and possibly spin. With input from the LHC and from indirect searches, direct detection experiments will hopefully allow us to determine the local density and to constrain the local phase-space structure of our DM halo. The scientists have been working for the past decade on this mission at the Canfranc Underground Laboratory, in Huesca, where they have developed various cryogenic detectors. The latest is a "scintillating bolometer", a 46-gram device that, in this case, contains a crystal "scintillator", made up of bismuth, germinate and oxygen, which acts as a DM detector.

5.1 Direct Detection of Dark matter

5.1.1 Energy transfer mechanism

In this technique the detector is constructed very deep underground to discard all the noises from CMB and cosmic rays and in such a way that DM particles should collide with the detector. And since it's found that the interaction between DM particles is less than 35kpc/h for a typical scattering cross section of 1.75×10^{-25} cm^2, the density of detector particles should be very high. The detector should be very cold to maximize the probability of collision so cryogenic detectors are used.

$$E = \frac{1}{2}mv^2\frac{Mm}{(M+m)^2}[2(1+cos\theta)]$$

Formula for Energy transfer (E) due to collision between two particles is mentioned above where m is the mass of DM particle, M = is mass of Detector particle, v = velocity of DM particle, θangle of scattering, Thus to get maximum Energy transfer we need $M \approx m$ and $\theta = 0$ (head on collision). So if the search is forWIMPs, then the best detector is Liquid Xenon whose mass of nuclei is approx the mass of WIMPs.

Example:- On May 2018 XENON1T instrument in Italy A giant container filled with XENON served as DM particles dragnets. The Large Underground Xenon (LUX) experiment tried to detect WIMPs particles by using a detector of 370 kg liq. Xenon, if any WIMPs collides it would produce Electroluminescent photons. After experimenting for two years, there was no result. But right now another detector with 3,500 kilograms of liq. Xenon at a depth of 1400 mts is working to detect WIMPs particles which have high probability of positive results. Other such Labs are SNOLAB, GSNL, CUL, BUL, DUSEL, PAXD, etc. Similar experiments are CDMS, XENON, ZEPLIN, WARP, ArDM, etc

5.1.2 Creating DM particles by mimicking conditions of the Early Universe

LHC is one of the best instruments to mimic the early universe which can create so much energy that matter (even DM particles) can be created. If a WIMPs particle of mass around 100GeV has to be created then The energy required to produce WIMPs should be 100GeV ($E=mc^2$). But even if WIMPs are produced, it can't be seen or read through radiation detectors directly. So another simple method of Conservation of Momentum is applied. Basically after the collision generally all particles scatter such that there is symmetry around the point of collision. But if WIMPs are produced and since, we can't see it, then it looks as if some detectable particles move in one direction only. Physicists could infer their existence from the amount of energy and momentum "missing" after a collision. Hence, it's confirmed that the WIMPs are created which are moving in another direction, but just that it can't be seen or detected. This is the way how LHC could create and detect DM particles.

5.1.3 Superconducting grains

Drukier and Stodolsky detected solar and reactor neutrinos by exploiting their elastic neutral-current scattering of nuclei in a detector made of superconducting grains embedded in a non-superconducting material. This detection influenced Goodman and Witten to the idea that WIMPs can be detected by elastic scattering off nuclei in a terrestrial detector. Drukier et al. extended this study to include a variety of cold DM candidates, as well as details of the detector and the halo model. They also showed that the Earth's motion around the Sun produces an annual modulation in the expected signal. Theoretically, many progress has been made in refining all aspects of entering the prediction of scattering event rates: from detailed cross section calculations in specific particle and nuclear physics models, to refined DM halo models that take into account uncertainties in the local WIMPs density, in their mean velocity and velocity distribution, as well as in the galactic escape velocity. Progress has been tremendous on the experimental side: side in developing new technologies that yield an increasing amount of information about every single particle interaction, in applying these technologies to detectors with masses soon to reach the ton-scale, and in fighting the background noise such that levels below 1 event per kilogram and year have now been reached.

5.2 Indirect Detection of Dark matter

Gamma rays have several unique properties that make them ideally suited to study DM annihilations. For example, they are not deflected by magnetic fields, which means they can serve as signposts back to wherever they were created, helping reveal the distribution of DM in the universe.

5.2.1 Detection at the center of milky way galaxy

The galactic center is expected to be the brightest source of gamma rays from dark matter annihilation by at least two orders of magnitude. However, the galactic center is also one of the most complex and difficult regions of the sky to model because of the strong diffuse emission and high density of gamma-ray sources. *The Fermi-Large Angle Telescope* (Fermi-LAT) is working to better understand the gamma-ray data from the galactic center region. This effort might yield the discovery of a DM signal or, in the absence of a signal, to key clues on the nature of DM.

5.2.2 Detection in Dwarf spheroidal galaxies

One ideal type of place to focus searches are dwarf spheroidal galaxies, where star formation is usually highly suppressed, making the gravitational signature of DM easy to model. Currently, there are roughly 25 known dwarf satellite galaxies to the Milky Way, and both ground-based instruments such as the *High-Energy Stereoscopic System* (HESS), *Major Atmospheric Gamma-ray Imaging Cherenkov* (MAGIC), and *Very Energetic Radiation Imaging Telescope Array* (VERITAS) as well as the *Fermi-LAT* (Large Area Telescope) are actively observing these objects.

As said one of the most promising sites in the search for DM is the center of our own galaxy. However, gamma rays from there may also emerge from a multitude of astrophysical sources, as well as from cosmic rays interacting with dense molecular clouds in the inner galaxy. Thus scientists believe that the smoking gun signature of DM will be gamma rays all of very specific wavelengths, a signal that is very difficult to mimic using astrophysical sources. Recently hopes were raised that such a signal may have been detected — gamma rays of 130 GeV and a very specific line of wavelengths in an extended region around the galactic center might be the long-awaited first clear evidence of DM annihilation into gamma rays.

6. CANDIDATES

6.1 Weak Interacting Massive Particles (WIMPs):

Year:1985

Mass: 1GeV to 1000 GeV

WIMPs are heavy (mass about 300 GeV), EM neutral, slow moving (Cold) and non- baryonic. Scientists theorised WIMPs 30 years ago to help explain why galaxies don't fly apart. WIMPs are particles that are about 100 times heavier than a proton. This prevailing theory helps attract normal matter into clumps that become galaxies that produce stars. Decades of research show that they interact rarely with one another. Hence they are termed weakly interacting. WIMPs with SubGeV masses may be considered to be light dark matter. The theory suggests that in the hot, early universe, pairs of WIMPs collided and annihilated each other , forming other particles though the reverse action is also taking place. It would likely be cold. Extraordinary efforts are under way to detect and measure the properties of WIMPs, either by witnessing their impact in a laboratory detector or by observing their annihilation after they collide with each other. The popularity of the theory stems from the wimp miracle, whose hypothesis is that, if wimps exist and are stable, then it is naturally produced with a relic density that is required of DM.

Supporting Theory:- 'SuperSymmetry' is a theory that suggests each elementary particle is associated with a super partner. In the standard model, no two particles are super partners. Hence, there has to be an undetected partner. So potentially, even WIMPs should have a super partner which could be making a super partner. Detecting either one of the particles establishes WIMPs.

Experiments :- LUX, LHC

<u>Failures</u>: Failed to explain the distribution of DM in small galaxies.

6.2 Strongly Interacting Massive Particles(SIMPs):

Year: 2014

Mass: ~0.1 Gev

Physicists: Hitoshi Murayama, Yonit Hochberg

SIMPs or Strongly Interacting Massive Particles is yet another theory of dark matter. This theory states that DM particles interact strongly among themselves. These particles are said to be made of an up quark and a down antiquark with strong nuclear force (gluons) binding them together. This theory was proposed as the solution for the ultra-high-energy cosmic ray problem as well as the absence of cooling flows in galactic clusters. SIMPs are composite particles made of other smaller particles as compared to protons and neutrons. As these are considered to be strongly interacting with one another, it explains two key astronomical observations that bucks against WIMPs.

(i) ***Colliding Galaxies (Bullet Cluster Formation)***

Here they inferred that; a great amount of DM had detached from the host galaxies in a celestial smashup happening some 1.4 billion light years away. This suggests that DM pushes against itself and cannot readily flow together with visible matter & gas, as WIMPs should.

(ii) ***Screwy distribution of DM within smaller galaxies***

Computer simulations show that due to gravity WIMP's should glue together, forming dense clumps of DM in the centre of galaxies. They also have to gather and form chunks out in space. But observations clash with the predictions. Galactically DM seems too evenly spread out, and astronomers have never found the chunks the WIMP model predicts.

Experimentation: '**SuperKEKB**' – Particle accelerator in Japan (started in April 2018) - This machine collides lightweight electrons and their antimatter counterparts, and from the detritus might fling out the occasional SIMPs.

6.3 Axions:

Year:1977

Mass: 1×10^{-15} Gev

Axions are non-baryonic particles that are hypothesized to be possible dark matter candidates. They were originally theorized in the year 1977 by Roberto Peccei and Helen Quinn, to explain the Strong Charge-Parity Problem. To solve this, particle physicists invented axions. Since Axions have all the properties of an ideal DM particle, it is considered to be a possible candidate.

- These don't behave differently when either their electric charges are switched or they get flipped upside down.
- To explain this unusual rigidness they came up with a way. As a side effect, the explanation suggested that the universe may be full of new hypothetical particles called 'Axions'.

Experiment: ADMX

- 13ft long metal cylinder sunk into the floor.
- It is just cooled above absolute zero to silence signal-masking perturbations.
- Magnet inside cranks out a powerful magnetic field.
- According to theory, they should convert any nearby axions to standard Radio Waves.
- These signals are roughly a billionth of a billionth of a billionth of a Watt each.
- For this ADMX has built the “Amplifier”(Most sensitive radio receiver ever built).

6.4 Sterile Neutrinos:

Mass: ~ 1GeV

This term usually refers to neutrinos with right-handed chirality, which may be added to the Standard Model. The existence of right-handed neutrinos is theoretically well-motivated, since all other known fermions have been observed with both left and right chirality. They could explain in a natural way, the small active neutrino masses inferred from neutrino oscillation. The mass of the right-handed neutrino is unknown and therefore could have any value between 10^{15} GeV and less than 1 eV.

Sterile neutrinos may be produced in a number of ways. The relic density depends on the sterile neutrino mass and mixing angle whose mechanisms require them to have a low mass as well as a low mixing angle.

Experiments during 1990’s

- Neutrinos come in 3 flavours (electron neutrino, muon neutrino, tau neutrino)
- These particles very rarely interact with matter with Weak Nuclear Forces.
- Theorists postulated that flavour skew arose because some neutrinos were morphing to the fourth sterile flavour, before returning to variety, electron neutrino.

About the experiment:

- The sensor-studded sphere is nearly 40 feet across, filled with over 800 tons of pure mineral oil. The instrument registers the flash of lights on the rare occasions when neutrinos produced in a nearby beam bump into mineral oil’s constituent atoms.
- Although assuming Sterile Neutrinos legit, they are neither sufficient in mass nor number to constitute the back of Dark Matter.

- It is assumed that multiple types of sterile neutrinos, with different masses may also exist.
- These results caught our brains in pondering about the existence of Dark Photons, Dark Quarks, Dark Gluons and other particles.

6.5 Dark Photons:

The Inhomogeneous universe could provide evidence for dark photons as a candidate for DM. Dark photons are force carriers similar to photons in electromagnetism. The fundamental parameter of this model is the mass of dark photon (gained by Higgs Interaction) and kinetic mixing. It is theoretically possible through misalignment mechanism.

7. Modified Newtonian Dynamics (MOND)

MOND was introduced by Milgrom in 1983. The theory is a modification to the Newtonian force law that changes the dynamics of interaction between two massive bodies in the non-relativistic limit. The MOND acceleration of gravity 'a' is related to the Newtonian acceleration a_N by

$$F_N = \mu\left(\frac{a}{a_0}\right) a \quad a_0 = \mu\left(\frac{a}{a_0}\right)$$

This theory tried to explain the anomaly by a modifying Newton's second law, according to which gravitational force on orbiting matter can be equated to a product of its mass and acceleration.

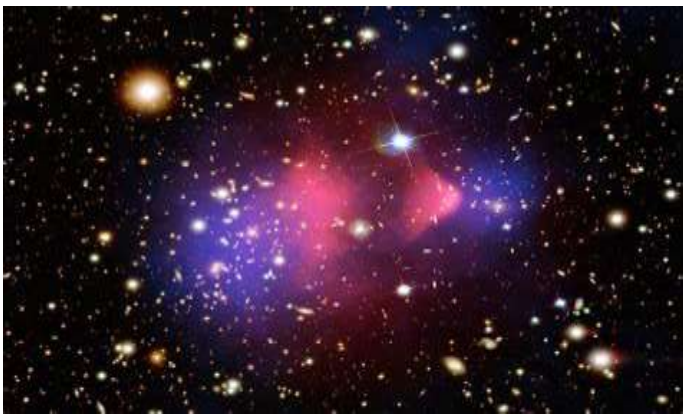
- F_N is the Newtonian force and 'm' is the mass of the body.
- a is its acceleration
- $\mu(x)$ is an as-yet unspecified function (called the *interpolating function*)
- a_0 is a universal acceleration scale whose value is accounted as 10^−8 cm/s^2. For accelerations much lower than this scale, the Newtonian law is modified, and this explains the flat galaxy rotation curve data for a large number of galaxies. It marks the transition between the Newtonian and deep-MOND regimes.

Also, at large radii, the dependence on gravity was modified to 1/r. Therefore, by this modification, the theory explains the reason for the flat rotational curves without the inclusion of the exotic DM.

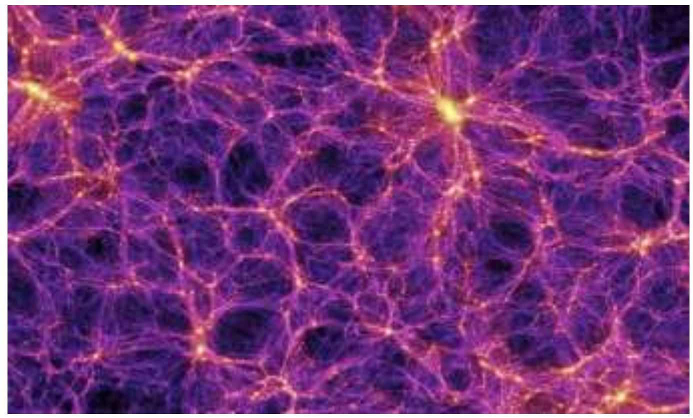
Although MOND is able to solve the flat-rotational curve problem, it does not answer other mysteries observed.

7.1: Failures of MOND

- The observation of the Bullet cluster: Most of the matter in the clusters was clearly separate from the gases that were heated up due to the collision. The gravitational lensed matter suggested that there was some other 'stuff' that held all of it together. MOND fails to explain this particular observation.
- The magnitude to which light is Gravitationally Lensed due to large Galactic Clusters exceeds the predicted amount of lensing based on the amount of baryonic matter in it. The solution to this observation too requires the presence of extra invisible mass.
- MOND does not account for the filament-like structures observed at the cosmic level.



The Bullet Cluster



Cosmic Filament Structure

Image Credits: Left: https://www.secretsofuniverse.in/bullet-cluster/
Right: http://www.sci-news.com/astronomy/milky-way-galaxy-cosmic-void-04939.html

These failures of the MOND theory strengthen the LCDM theory that strongly predicts the presence of DM in the Universe and thereby leading us to a DM Hunt.

8.Conclusion

Humanity might be on the threshold of a humongous discovery as the experimental and observational capabilities have progressed to the point where the search for dark matter is carried out with highly sensitive instruments. This involves the testing of the hypothetical candidates of DM such as WIMPs, SIMPs, Axions, Sterile Neutrinos and many others. The very idea that we might detect DM either in an accelerator like the LHC at CERN or indirectly via experiments such as ADMX, AMS, Fermi and IceCube is quite exciting.

DM candidates arise frequently in theories that suggest physics beyond the Standard Model, such as supersymmetry and extra dimensions. Theories also suggest the existence of a "Hidden

Valley", a parallel world made of DM having very little in common with the matter you and I are made of.

Looking for evidence from the infant universe to the present day by observing the CMB, mighty galactic structures and the very horizon of the observable universe, we are yet to unfold the universe's dark secrets. If various unique observations lead to the same result, that theory can't be neglected. The same occurs in the case of DM. The Dark matter theory can't be neglected until proven wrong!

'Somewhere, Something Incredible is waiting to be known.'

- Carl Sagan

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