A PROJECT REPORT ON

DARK MATTER

BY

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UNDER THE SUPERVISION OF

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ABSTRACT

For centuries scientists have looked up at the night sky and believed that the luminous matter was all that made up our Universe. This belief has been challenged in the past hundred years due to experiments that have shown that our Universe cannot be in its present configuration without the presence of some unknown type of matter. This unknown matter is supposed to be dark matter.

We have strong indirect evidence for dark matter but it has not been observed directly till date. The search for dark matter is about more than explaining discrepancies in observation of the Universe which we cannot explain with our present understanding. Dark matter will help us to answer the questions about how the universe formed, and how it will ultimately end.

In this report I have tried to explain what dark matter is (or what it is not), its history and how experiments are being conducted to search for this elusive dark matter. This report has been composed in a way such that any student at the undergraduate level can easily grasp the concept of dark matter.

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INTRODUCTION

Mankind is quite obsessed with explaining our existence, from justifying our nationality to justifying the universe and our place in it. So, while it is certainly difficult to attempt to map the universe because of its size, it is even more difficult to try to explain away matter in the universe that cannot be observed directly, matter that seems invisible because it does not emit light, but we know exists. Such matter is called dark matter, and for the majority of the 20th Century its discovery and research have dominated the field of cosmology. [3]

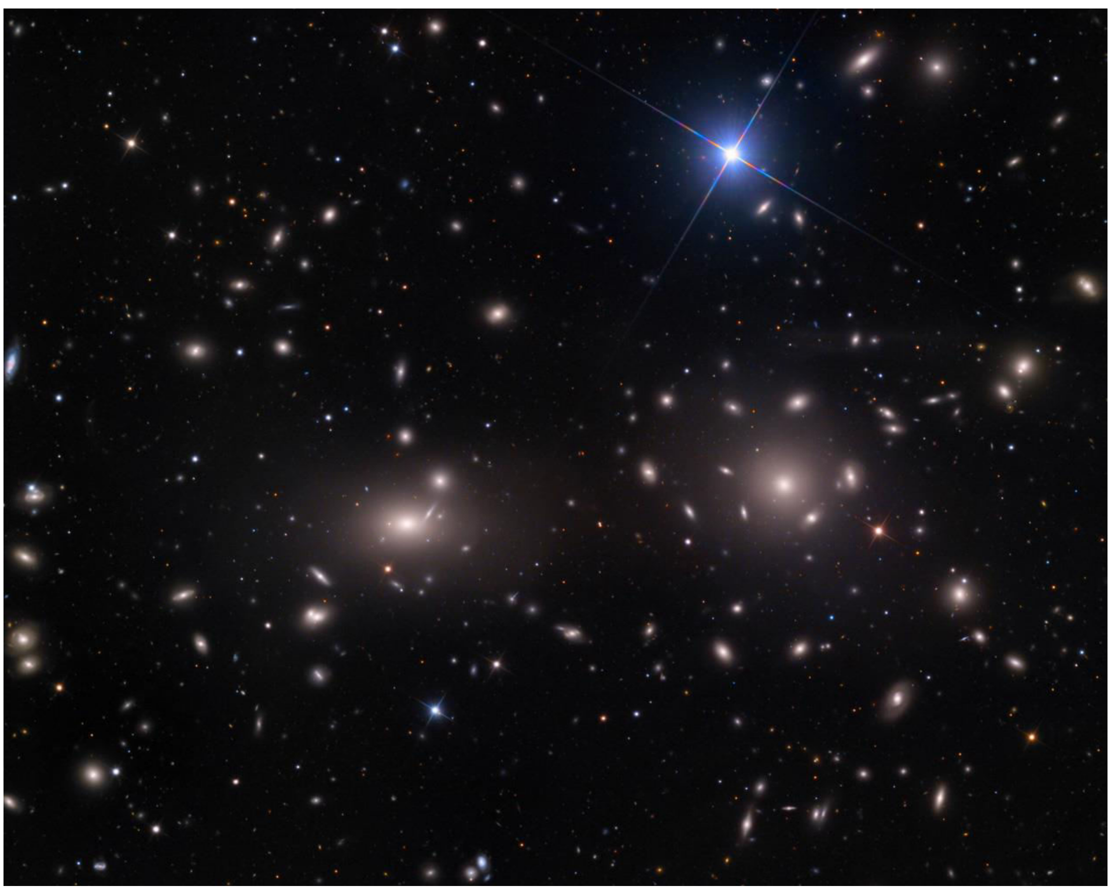
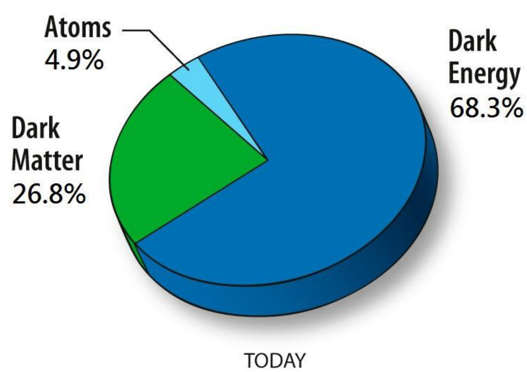


Fig. - It is embarrassing to note that we don't know much about 90% of the matter that makes up the Universe (in the form of dark matter). Above is an image of the Coma cluster which contains about 90% dark matter (other than the luminous matter). [10]

Dark matter is matter in the universe that we cannot see directly because it does not emit light. However, we know dark matter exists because of how its gravity affects other universal bodies, like stars and galaxies. Dark matter's existence is known from gravitational effects on visible matter and gravitational lensing of background radiation. It was originally hypothesized to account for discrepancies between calculations of the mass of galaxies, clusters of galaxies and the entire universe made through dynamical means (by measuring the speed of the galaxies), and calculations based on the mass of the visible "luminous" matter these objects contain (by measuring the luminosity and hence the mass).

The most widely accepted explanation for these phenomena is that dark matter exists and that it is most probably composed of a new type of particle called the “weakly interacting massive particles” (WIMPs) that interact only through gravity and the weak force. Alternative explanations have been proposed but there is not yet sufficient experimental evidence to determine which is correct.

According to observations, dark matter accounts for 26.8% of the mass-energy content of the observable universe. In comparison, ordinary (baryonic) matter accounts for only 4.9% of the mass-energy content of the observable universe, with the remainder being attributable to dark energy. From these figures, matter accounts for 31.7% of the mass-energy content of the universe and 84.5% of the matter is dark matter.



Dark matter plays an important role in computer simulations and modeling of cosmic structure formation and Galaxy formation and evolution and has measurable effects on the anisotropies (irregularities) observed in the cosmic microwave background. All these lines of evidence suggest that galaxies, clusters of galaxies, and the universe as a whole contain far more matter than that which interacts with electromagnetic radiation.

Important as dark matter is thought to be in the cosmos, direct evidence of its existence and a concrete understanding of its nature has remained elusive. Though the theory of dark matter remains the most widely accepted theory to explain the anomalous observations, some alternative theoretical approaches have been developed which broadly fall into the categories of modified gravitational laws and quantum gravitational laws. [4]

We are much more certain what dark matter is “not” than we are what it is. First, it is dark, meaning that it is not in the form of stars and planets that we see. Observations show that there is far too little visible matter in the Universe to make up the 26.8% required by the observations. Second, it is not in the form of dark clouds of normal matter, matter made up of particles called “baryons”. We know this because we would be able to detect baryonic clouds by their absorption of radiation passing through them. Third, dark matter is not antimatter, because we do not see the unique gamma rays that are produced when antimatter annihilates with matter. Finally, we can rule out large galaxy-sized black holes on the basis of how many gravitational lenses we see. High concentrations of matter bend light passing near them from objects further away (gravitational lensing), but we do not see enough lensing events to suggest that such objects to make up the required 26.8% dark matter contribution.

However, at this point, there are still a few dark matter possibilities that are viable. Baryonic matter could still make up the dark matter if it were all tied up in brown dwarfs or in small, dense chunks of heavy elements. These possibilities are known as massive compact halo objects, or "MACHOs". But the most common view is that dark matter is not baryonic at all, but that it is made up of other, more exotic particles like axions or WIMPS (Weakly Interacting Massive Particles). [5]

EVIDENCE

The first signs

The first detection of dark matter is attributed to Fritz Zwicky (1933), who measured the velocity dispersion of galaxies in the Coma cluster and found their velocities to far exceed that which could be attributed to the luminous matter in the galaxies themselves. [6]

He looked at velocity measurements of several individual galaxies in the Coma cluster and noticed that the galaxies seemed to be moving too fast for the amount of visible matter in the cluster. If one adds up the mass in the cluster by assuming that every galaxy has a mass-to-light ratio of about one in solar units, then there isn't enough mass to hold the cluster together, i.e., the galaxies should fly apart.

Mass to light ratio – Mass to light ratio is the quotient between the total mass of a spatial volume (galaxy or cluster) and its luminosity. These ratios are often reported using the value of mass to light ratio calculated for the Sun as a baseline ratio which is a constant (approximately equal to 5133kg/W).

Zwicky estimated the cluster's total mass based on the motions of galaxies near its edge (using the virial theorem) and compared that estimate to one based on the number of galaxies and total brightness of the cluster. He found that there was about 400 times more estimated mass than was visually observable. The gravity of the visible galaxies in the cluster would be far too small for such fast orbits, so something extra was required. This is known as the "missing mass problem". Based on these conclusions, Zwicky inferred that there must be some non-visible form of matter which would provide enough of the mass and gravity to hold the cluster together.

Galaxy rotation curves

For nearly four decades the “missing mass problem” was ignored, until Vera Rubin in the late 1960s and early 1970s measured velocity curves of edge-on spiral galaxies to a theretofore unprecedented accuracy. To the great astonishment of the scientific community, she demonstrated that most stars in spiral galaxies orbit the center at roughly the same speed, which suggested that mass densities of the galaxies were uniform well beyond the location of most of the stars. This was consistent with the spiral galaxies being embedded in a much larger halo of invisible mass (“dark matter halo”). [7]

An influential paper presented Rubin's results in 1980. Rubin's observations and calculations showed that most galaxies must contain about six times as much “dark” mass as can be accounted for by the visible stars. Eventually other astronomers began to corroborate her work and it soon became well-established that most galaxies were dominated by "dark matter".

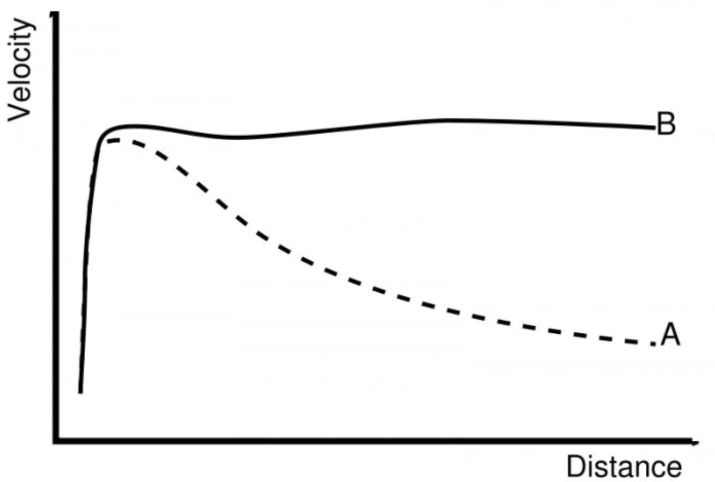
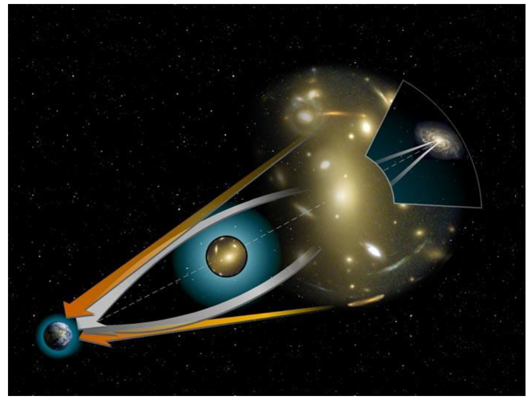


Fig. - A typical galaxy rotation curve. A is the expected curve.
B is the observed curve. (Distance is measured from the centre of the galaxy.) [11]

Fig. – An artist’s impression is shown of a galaxy embedded in a halo of dark matter particles. [12]

Gravitational Lensing

Gravitational Lensing – In general relativity, the presence of matter (energy density) can curve spacetime, and the path of a light ray will be deflected as a result. This process is called gravitational lensing and in many cases can be described in analogy to the deflection of light by lenses in optics.



Another important tool for dark matter observations is gravitational lensing. Lensing relies on the effects of general relativity to predict masses without relying on dynamics, and so is a completely independent means of measuring the dark matter.

Strong lensing, the observed distortion of background galaxies into arcs when the light passes through a gravitational lens, has been observed around a few distant clusters. By measuring the distortion geometry, the mass of the cluster causing the phenomena can be obtained. In the dozens of cases where this has been done, the mass-to-light ratios obtained correspond to the dynamical dark matter measurements of clusters. Weak gravitational lensing looks at minute distortions of galaxies observed in vast galaxy surveys due to foreground objects through statistical analyses. By examining the apparent shear deformation of the adjacent background galaxies, astrophysicists can characterize the mean distribution of dark matter by statistical means and have found mass-to-light ratios that correspond to dark matter densities predicted by other large-scale structure measurements. The correspondence of the two gravitational lens techniques to other dark matter measurements has convinced almost all astrophysicists that dark matter actually exists as a major component of the universe's composition.

The most direct and promising observational evidence to date for dark matter is in a system known as the Bullet Cluster. In most regions of the universe, dark matter and visible material are found together, as expected because of their mutual gravitational attraction. In the Bullet Cluster, a collision between two galaxy clusters appears to have caused a separation of dark matter and baryonic matter. X-ray observations show that much of the baryonic matter (in the form of 10^7–10^8 K gas, or plasma) in the system is concentrated in the center of the system. Electromagnetic interactions between passing gas particles caused them to slow down and settle near the point of impact. However, weak gravitational lensing observations of the same system show that much of the mass resides outside of the central region of baryonic gas. Because dark matter does not interact by electromagnetic forces, it would not have been slowed in the same way as the X-ray visible gas, so the dark matter components of the two clusters passed through each other without slowing down substantially. This accounts for the separation.

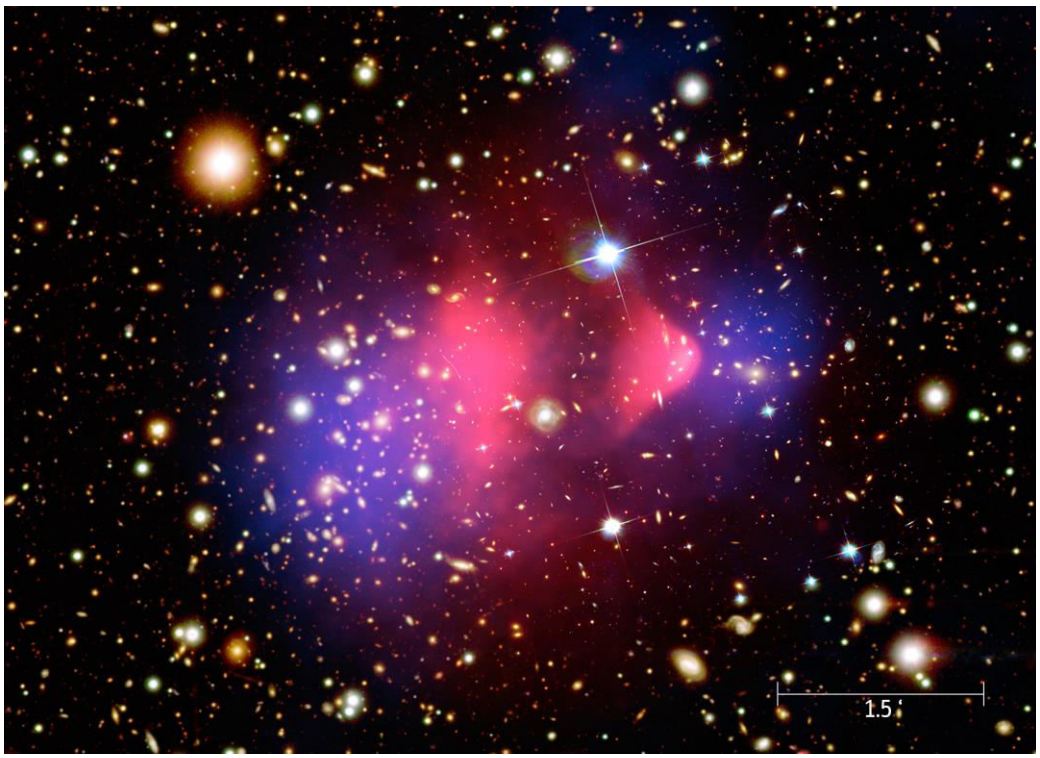


Fig. – The Bullet Cluster (two galaxies colliding). The image has red and blue overlays. The red part is the hot gas which has smashed up against each other and formed a shockwave. The blue part is the dark matter which passes through without interacting. [13]

Unlike the galactic rotation curves, this evidence for dark matter is independent of the details of Newtonian gravity, so it is claimed to be direct evidence of the existence of dark matter. Also, the distribution of dark matter in merging clusters such as the Bullet Cluster shows that dark matter scatters off other dark matter particles only very weakly if at all.

Cosmic Microwave Background Radiation (CMBR)

Cosmic Microwave Background Radiation – The cosmic background radiation is electromagnetic radiation that fills the Universe. The radiation can only be detected with a radio telescope which makes it show as a faint glow. This glow is strongest in the microwave area of the spectrum.

When the Universe was (relatively) young, the protons and electrons and photons formed a dense plasma. The photons could not travel much as they scattered off the free electrons and protons. But as the Universe expanded, it cooled. When the protons and electrons combined to form neutral atoms like hydrogen and helium (known as the recombination epoch), the photons decoupled and started travelling freely. They were emitted at a temperature of 3000K but as the Universe started to expand they cooled and hence their wavelengths shifted. We now observe them at a temperature of about 2.725K.

There are also anisotropies measured in the CMBR. These are caused due to difference in baryon density at the time of recombination.

Angular fluctuations in the cosmic microwave background (CMB) spectrum provide evidence for dark matter. Since the 1964 discovery and confirmation of the CMB radiation, many measurements of the CMB have supported and constrained this theory. The NASA Cosmic Background Explorer (COBE) found that the CMB spectrum is a blackbody spectrum with a temperature of 2.726 K. In 1992, COBE detected fluctuations (anisotropies) in the CMB spectrum, at a level of about one part in 10^5. During the following decade, CMB anisotropies were further investigated by a large number of ground-based and balloon experiments. The primary goal of these experiments was to measure the angular scale of the first acoustic peak of the power spectrum of the anisotropies, for which COBE did not have sufficient resolution. In 2000–2001, several experiments, most notably BOOMERanG found the Universe to be almost spatially flat by measuring the typical angular size (the size on the sky) of the anisotropies. During the 1990s, the first peak was measured with increasing sensitivity and by 2000 the BOOMERanG experiment reported that the highest power fluctuations occur at scales of approximately one degree.

COBE's successor, the Wilkinson Microwave Anisotropy Probe (WMAP) has provided the most detailed measurements of (large-scale) anisotropies in the CMB as of 2009. WMAP's measurements played the key role in establishing the current Standard Model of Cosmology, namely the Lambda-CDM model, a flat universe dominated by dark energy, supplemented by dark matter and atoms with density fluctuations seeded by a Gaussian, adiabatic, nearly scale invariant process. The basic properties of this universe are determined by five numbers: the density of matter, the density of atoms, the age of the universe (or equivalently, the Hubble constant today), the amplitude of the initial fluctuations, and their scale dependence.

A successful Big Bang cosmology theory must fit with all available astronomical observations, including the CMB. In cosmology, the CMB is explained as relic radiation from shortly after the big bang. The anisotropies in the CMB are explained as acoustic oscillations in the photon-baryon plasma (prior to the emission of the CMB after the photons decouple from the baryons at 379,000 years after the Big Bang) whose restoring force is gravity. Ordinary (baryonic) matter interacts strongly with radiation whereas, by definition, dark matter does not. Both affect the oscillations by their gravity, so the two forms of matter will have different effects. The typical angular scales of the oscillations in the CMB, measured as the power spectrum of the CMB anisotropies, thus reveal the different effects of baryonic matter and dark matter. The CMB power spectrum shows a large first peak and smaller successive peaks, with three peaks resolved as of 2009.[55] The first peak tells mostly about the density of baryonic matter and the third peak mostly about the density of dark matter, measuring the density of matter and the density of atoms in the universe.

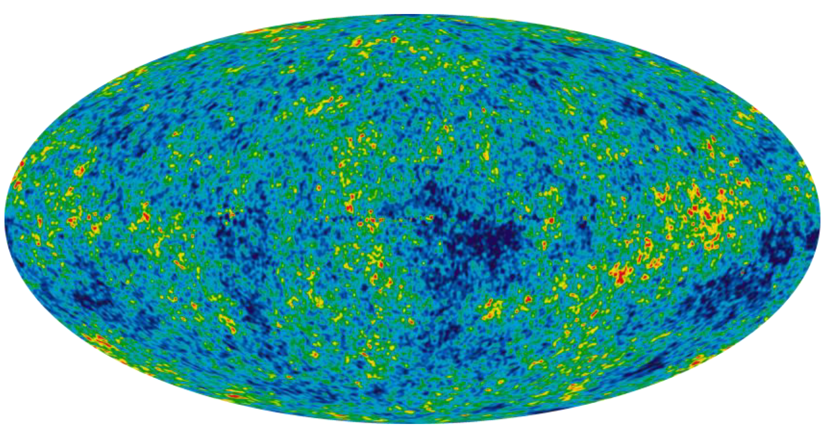


Fig. – WMAP’s All Sky Map of the CMB. The fluctuations are at a level of 10 µK. [14]

Baryon Acoustic Oscillations

Baryon Acoustic Oscillations – Baryon Acoustic Oscillations (BAO) are the periodic fluctuations in the density of the baryonic matter in the Universe, caused by acoustic waves which existed in the early Universe.

The early Universe consisted of hot and dense plasma of baryons and photons. Photons could not travel large distances because they were trapped in this plasma. Now suppose there is an overdense region in this primordial plasma. This overdensity gravitationally attracts matter towards it but the heat of the photon-baryon interactions creates a large amount of outward pressure. These opposing forces of gravity and pressure create oscillations, like sound waves created by pressure differences.

Consider a single wave originating in a region. The region consists of dark matter, baryons and photons. The pressure results in a spherical sound wave consisting of baryons and photons moving outwards from the overdensity. The dark matter remains at the overdensity (the centre) because it interacts only gravitationally. When the decoupling of photons and baryons happens, the photons diffuse away leaving a shell of baryonic matter at a fixed radius. This radius is known as the sound horizon. Therefore there are overdensities at the center and at the sound horizon. These overdensities continue to attract matter and form galaxies. So one would expect most galaxies to be separated by the sound horizon. There were many such waves, so the Universe consists of overlapping waves. We can measure this effect by looking at the separations of large number of galaxies.

The baryon acoustic oscillations in the early universe leave their imprint in the visible matter by clustering, in a way that can be measured with sky surveys such as the Sloan Digital Sky Survey and the 2dF Galaxy Redshift Survey. These measurements are consistent with those of the CMB derived from the WMAP spacecraft and further constrain the Lambda CDM model and dark matter.

Large scale structure formation of the Universe

Dark matter is an essential component of the Big Bang model. A significant amount of non-baryonic cold dark matter is necessary to explain the large scale structure of the Universe.

Observations suggest that structure formation in the universe proceeds in order, with the smallest structures collapsing first and followed by galaxies and then clusters of galaxies. As the structures collapse in the evolving universe, they begin to "light up" as the baryonic matter heats up through gravitational contraction and the object approaches hydrostatic pressure balance. Ordinary baryonic matter had too high a temperature, and too much pressure left over from the Big Bang to collapse and form smaller structures. Dark matter acts as a compactor of structure. This model not only corresponds with statistical surveying of the visible structure in the universe but also corresponds precisely to the dark matter predictions of the cosmic microwave background.

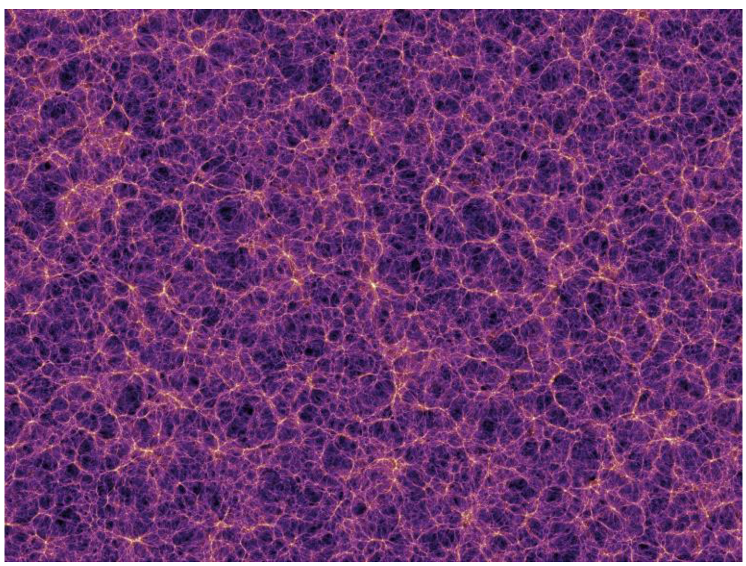


Fig. – A image from the Millennium Simulation of the Universe. [15]

This model of structure formation requires something like cold dark matter to succeed. Large computer simulations of billions of dark matter particles have been used to confirm that the cold dark matter model of structure formation is consistent with the structures observed in the universe through galaxy surveys, such as the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey. These studies have been crucial in constructing the Lambda-CDM model which measures the cosmological parameters, including the fraction of the universe made up of baryons and dark matter.

The computer simulation was done a supercomputer in Germany. The supercomputer created a simulation of the large-scale structure of the universe by first examining the data from NASA's WMAP explorer, which maps out the cosmic microwave background radiation. Since this radiation is the light left over from the Big Bang, it's the most ancient data in the universe, and from those starting conditions the supercomputer can use existing theoretical knowledge to simulate the evolution of different parts of the universe. Because the supercomputer's results match up almost perfectly with what we actually can observe of the history of the cosmos, astronomers are confident in its accuracy as a proxy for the actual universe.

Dark matter is a key part of the simulation - it would have to be, considering it accounts for 26.8% of everything in the universe. The simulation relies on a theoretical model known as the Lambda Cold Dark Matter model, which says that gravity began pulling bits of dark matter together into clumps shortly after the Big Bang. These clumps became larger and larger over time, attracting regular matter to form galaxies around them.

DETECTION EXPERIMENTS

Dark matter cannot consist of baryons. There are two lines of evidence for this. First, if baryons made up all the dark matter, the cosmic microwave background and cosmic web of structure would look radically different. Second, the abundance of light elements created during big-bang nucleosynthesis depends strongly on the baryon density (more precisely, on the baryon-to-photon ratio) of the Universe. Observed abundances of deuterium and ^{4}He constrain give similar constraints on the baryon density in the Universe as those coming from cosmic microwave background observations. These lines of evidence imply that a once-popular class of baryonic dark-matter candidate, the Massive Compact Halo Object (MACHOs) class (e.g., brown dwarfs, stellar remnants) is cosmologically insignificant. [8]

Massive Compact Halo Objects (MACHO) – It is an explanation for dark matter. MACHO is a body made of baryonic matter which emits little or no light. They consist of black holes, neutron stars, brown dwarf stars.

Among the non-baryonic candidates there are several classes of particles which are distinguished by how they came to exist in large quantity during the early Universe, and also how they are most easily detected. The axion is mentioned as a possible solution to the strong CP problem and is in a class by itself. The largest class is the Weakly Interacting Massive Particle (WIMP) class, which consists of literally hundreds of suggested particles. The most popular of these WIMPs is the neutralino from supersymmetry. The key features of this particle class are exactly as described: interactions around or near typical weak-force interactions (the fine-structure constant α near the weak-scale coupling ~ 10^{-2}), particle masses near the weak scale (m ~ 100 GeV in particle-physics units, similar to the mass of a silver atom).

Another important categorization scheme is the hot vs. cold classification. A dark matter candidate is called "hot" if it was moving at relativistic speeds at the time when galaxies could just start to form. It is called "cold" if it was moving non-relativistically at that time. This categorization has important ramifications for structure formation, and there is a chance of determining whether the dark matter is hot or cold from studies of galaxy formation. Hot dark matter cannot cluster on galaxy scales until it has cooled to non-relativistic speeds, and so cold dark matter is the preferred alternative.

> **Lambda-CDM model** – It is a cosmological model for explaining the Universe which consists of the cold dark matter and dark energy (the cosmological constant or lambda). The model is known as the Standard Model of Cosmology as it provides a good match to many astronomical observations (the CMBR, the large scale structure of the Universe, the accelerating expansion of the Universe).

Since WIMPs are the most popular class of dark-matter candidate (or at least the class which gets the most experiments), I will describe WIMP searches here. There are three main strategies for detecting dark matter particles – producing them in accelerators (collider searches), direct detection and indirect detection.

Collider Searches

WIMPs will not directly be observed if they are created at colliders–given that they are neutral and weakly interacting. However, it is possible to infer their existence. The quarks and gluons in the protons smashed together at the LHC typically do not annihilate directly to WIMPs—since WIMPs belong to entire theories beyond the Standard Model, there are a variety of other extra particles to which quarks and gluons may annihilate. Those other particles may eventually decay to WIMPs inside the detector, the signature of which is missing energy when one tries to reconstruct the chain of events. There is not yet experimental evidence of physics beyond the Standard Model. Even if evidence for a WIMP is eventually found, we will not know if that particle is stable on timescales longer than a nanosecond. [8]

Direct Detection

A solution to the dark matter problem would be the detection of WIMPs from our Galactic halo as they move past and through the Earth. This would also allow measurement of the local density of dark matter and establish beyond doubt that the dark matter is non-baryonic cold dark matter. Since we roughly know the speed (~220 km s^{-1}) and the density (ρ~0.3 proton masses cm^{-3}), we can say that for a WIMP of mass of order 10–100 GeV, roughly 100000 dark matter particles per second pass through every square centimeter of the Earth. However, if WIMPs exist, they are very weakly interacting particles, so it is quite rare that one of them will interact at all; most of them pass right through the Earth unimpeded. In addition, if a WIMP does elastically scatter off a nucleus, the deposited energy is usually in the keV to 100 keV range, too small to be noticed except by exquisitely sensitive equipment. These difficulties, however, have not stopped many groups throughout the world from developing devices capable of detecting WIMPs. The detection rates turn out to be within and just beyond the reach of current experimental efforts.

The basic idea is to detect the small energy deposited when a WIMP scatters off a nucleus in some well instrumented piece of material. When a WIMP scatters off a nucleus in a crystal, the nucleus recoils, causing dislocation in the crystal structure, vibrations of the crystal lattice (i.e. phonons or heat) and also ionization. These signals can be detected. Another possibility is to use noble liquid detectors which detect the flash of scintillation light produced by a particle collision in liquid xenon or argon.

The main difficulties in these experiments come from the fact that the WIMP events are rare and that there are many backgrounds that deposit similar amounts of energy on much more frequent time-scales. Thus the experiments operate deep underground, where ionizing cosmic rays are less frequent, and typically operate their detectors at extremely cold temperatures to keep thermal excitations low. Also many types of shielding, as well as redundant detection methods are now becoming standard. Even so, these are difficult experiments and tiny amounts of radioactivity in the detector or shielding can swamp the expected signal. With effort, a background rate of less than one event per kilogram of detector per day can be achieved. The expected signal is highly dependent on the supersymmetry model, but typically is in the range from 10^{-5}–10 events kg^{-1} day^{-1}.

The events can be separated from the background in two ways. In some detectors the background (non-WIMP) interactions can be recognized and simply ignored. In the larger detectors this is not possible, so they use the fact that the WIMP event rate is predicted to be larger in June than in December. This annual modulation in event rate is caused by the Earth's orbit either being aligned with the Sun's motion in the Galaxy (in June) or anti-aligned (in December). The current generation of detectors has detection thresholds of around 1 event kg^{-1} day^{-1}, with hopes that within the next few years signals as small as 10^{-2} events kg–1 day–1 will be detectable. Thus there is a reasonable chance that dark matter neutralinos will be detected by this type of direct detection within the next few years. It is also clear, however, that there are many values of the supersymmetry parameters that predict detection rates of below the 10^{-2} events kg^{-1} day^{-1} threshold, and so would not be detectable in the near future by these methods.[9]

The cryogenic detector experiments (done using the recoil technique) include: CDMS, CRESST and EDELWEISS. Noble liquid experiments include ZEPLIN and XENON. Other experiments include the DAMA/NaI and DAMA/LIBRA experiments.

Cryogenic Dark Matter Search (CDMS)

CDMS uses cryogenic germanium and silicon detectors, which are capable of detecting weakly interactive dark matter (WIMPs). WIMPs are detected through their interactions with the nuclei in the germanium. When a nucleus is hit, it recoils, causing the whole germanium crystal to vibrate. These vibrations, or phonons, propagate to the surface of the crystal where heat sensors pick them up. There are other particles that will go through the detectors besides WIMPs. The CDMS detectors are shielded to minimize the number of these other particles. The detectors are capable of discriminating between most of them and the WIMP signal.

Fig. – The silicon-germanium detector. [16]

In April 2013, physicists from the CDMS reported having detected three events with the characteristics expected of dark matter particles. A statistical fluctuation of the experimental background is likely to produce three or more events resembling this result a little over 5% of the time. However, all three of these events have energies more like those expected of a low-mass dark-matter particle, something that should happen by chance only 0.19% of the time. This consideration brings the result to a higher confidence level, around 3 sigma. But still it cannot be considered a discovery. A discovery by scientific standards comes at 5 sigma.

XENON Dark Matter Search Experiment

The XENON Dark Matter Search Experiment aims to detect dark matter by looking for rare interactions via nuclear recoils in a liquid xenon target. It is a dual phase liquid Xenon time projection chamber (LXeTPC): the target volume is placed within the strong electric field of the TPC. Two arrays of photomultipliers (PMT) below and above the field are used to detect both, the direct scintillation light (S1) in the liquid Xe and ionization, via proportional scintillation in the Xe gas phase (S2). The liquid-gas border is located between the upper end of the TPC and the top PMT array. The ratio of the two signals, S1/S2, is different for electron and nuclear events providing an effective background discrimination method.

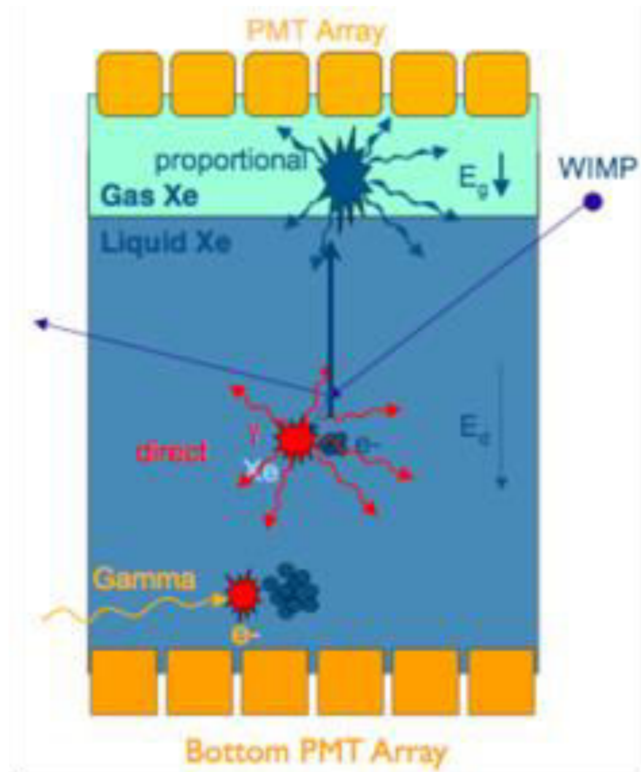


Fig. – A cross section and schematic description of the XENON100 experiment. [17]

In 2012, scientists from the XENON collaboration announced a new result from their search for dark matter. The analysis of data taken with the XENON100 detector during 13 months of operation at the Gran Sasso Laboratory (Italy) provided no evidence for the existence of WIMPs. Two events being observed are statistically consistent with one expected event from background radiation. Compared to their previous 2011 result the world-leading sensitivity has again been improved by a factor of 3.5. This constrains models of new physics with WIMP candidates even further and it helps to target future WIMP searches.

DAMA/LIBRA

The DAMA/LIBRA experiment is designed to detect dark matter using the direct detection approach, by using a scintillation detector to search for WIMPs in the galactic halo. The experiment aims to find an annual variation of the number of detection events, caused by the variation of the velocity of the detector relative to the dark matter halo as the Earth orbits the Sun. The experimental set-up is located at the Laboratori Nazionali del Gran Sasso in Italy. The detector is made of 25 highly radiopure scintillating thallium-doped sodium iodide (NaI (Tl)) crystals placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low background photomultipliers.

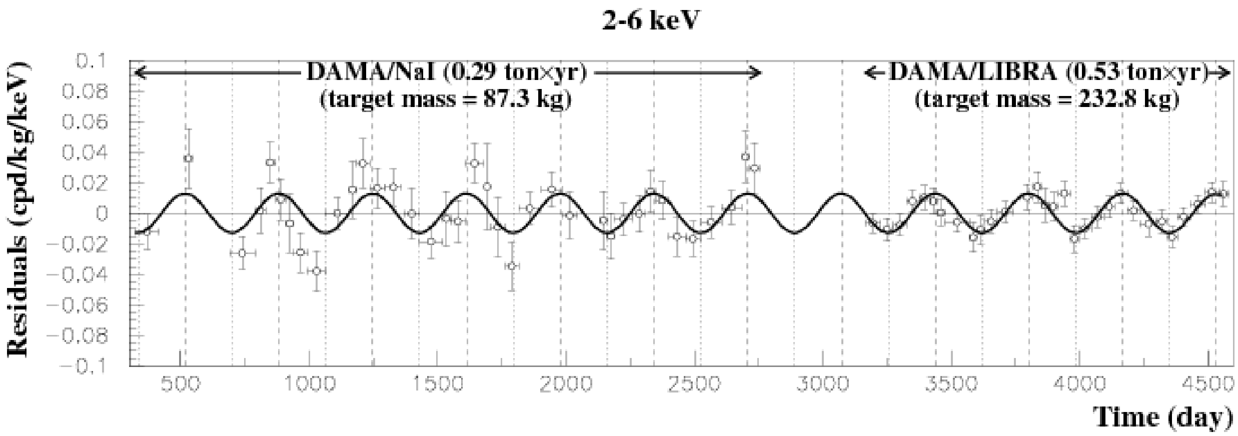


Image Courtesy – DAMA/LIBRA experiment

The DAMA/LIBRA data released so far correspond to 6 annual cycles. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles, the total exposure (1.17 ton x yr) has been collected over 13 annual cycles. This experiment has further confirmed the presence of a model independent positive evidence with high statistical significance on the basis of the exploited Dark Matter signature. Careful investigations on absence of any significant systematics or side reaction effect in DAMA/LIBRA have been quantitatively carried out. No systematics or side reactions able to mimic the signature has been found or suggested by anyone over more than a decade. The result is conclusive but since other experiments seem to contradict its results hence it is not widely accepted.

Indirect Detection

A great deal of theoretical and experimental effort has gone into another potential technique for WIMP detection. The idea is that if the halo is made of WIMPs, then these WIMPs will have been passing through the Earth and Sun for several billion years. Since WIMPs will occasionally elastically scatter off nuclei in the Sun or Earth, they will occasionally lose enough energy, or change their direction of motion enough, to become gravitationally captured by the Sun or Earth. The orbits of such captured WIMPs will repeatedly intersect the Sun (or Earth) resulting in the eventual settling of the WIMPs into the core. As the number density increases over time, the self annihilation rate will increase. Since ordinary neutrinos can result from WIMP self-annihilation, one predicts a stream of neutrinos coming from the core of the Sun or Earth. Neutrinos easily escape the solar core. Also WIMP annihilation can result in gamma rays, antiprotons or positrons.

Fermi Gamma Ray Space Telescope (FGST)

The Fermi Gamma-Ray Space Telescope, launched June 11, 2008, is searching for gamma rays from dark matter annihilation and decay. The Large Area Telescope (LAT) on board the Fermi satellite has been searching for this so-called annihilation signature since it was launched; so far, no dice. Part of the reason we may not have detected this signal yet is that it is not as simple as pointing Fermi towards the biggest nearby clump of dark matter and waiting to see something. The most obvious place to search for an annihilation signature is the Galactic Center, but that region unfortunately hosts a number of other interesting and gamma-ray-emitting objects. So another place to look is outwards, towards the dwarf spheroidal satellites orbiting the Milky Way. These small satellites have had most of their stars stripped away, because their gravity is not strong enough to hold them in long, but the dark matter remains more or less intact. Thus we ought to see a dark matter signal emanating from these cores – weaker than that from our galaxy, but less obscured as well, and not confused by as many other baryonic (normal stuff) sources. There have been a few claims of observations which can be accounted for by the dark matter particles but none of them have gained acceptance yet.

ALTERNATIVE THEORIES

Not everyone is sold on dark matter. A few astronomers believe that the laws of motion and gravity, formulated by Newton and expanded by Einstein, may have finally met their match. If that's the case, then a modification of gravity, not some unseen particle, could explain the effects attributed to dark matter.

The earliest modified gravity model to emerge was Milgrom's Modified Newtonian Dynamics (MOND) in 1983, which adjusts Newton's laws to create a stronger gravitational field when gravitational acceleration levels become tiny (such as near the rim of a galaxy). It had some success explaining galactic scale features, such as rotational velocity curves of elliptical galaxies, and dwarf elliptical galaxies, but did not successfully explain galaxy cluster gravitational lensing. However, MOND was not relativistic, since it was just a straight adjustment of the older Newtonian account of gravitation, not of the newer account in Einstein's general relativity. Soon after 1983, attempts were made to bring MOND into conformity with General Relativity; this is an ongoing process, and many competing hypotheses have emerged based around the original MOND model. But this theory is now in its dying stages.

Recently, another group has proposed a modification of large scale gravity in a hypothesis named "dark fluid". In this formulation, the attractive gravitational effects attributed to dark matter are instead a side-effect of dark energy. Dark fluid combines dark matter and dark energy in a single energy field that produces different effects at different scales. It hypothesizes that the fabric of space acts much like a fluid. Space would flow, coagulate, compress, or expand just like any other fluid. The idea is that when space is in the presence of matter, it slows down and coagulates around it; this then attracts more space to coagulate around it, thus amplifying the force of gravity near it. The effect is always present, but only becomes noticeable in the presence of a really large mass such as a galaxy. If this effect sounds very much like a description of dark matter, then that's not a coincidence, as a special case of the equations of dark fluid reproduces dark matter. But the theory of dark fluid does not hold that actual particles of dark matter exist, but rather that this is just an illusionary effect of space bunching up on itself.

On the other extreme, in places where there is relatively little matter, as in the voids between galactic superclusters, the theory of dark fluid predicts that space relaxes, and starts stretching away from itself. Thus dark fluid becomes a repulsive force, with the same effect as dark energy.

Still other alternatives regard dark matter as an illusion resulting from quantum physics. In 2011, Dragan Hajdukovic at the CERN proposed that empty space is filled with particles of matter and antimatter that are not only electrical opposites, but also gravitational opposites. With different gravitational charges, the matter and antimatter particles would form gravitation dipoles in space. If these dipoles formed near a galaxy – an object with a massive gravitational field – the gravitational dipoles would become polarized and strengthen the galaxy's gravitational field. This would explain the gravitational effects of dark matter without requiring any new or exotic forms of matter.

CONCLUSION

Dark matter plays a role in the fate of the Universe. The Universe is expanding, but will it expand forever? Gravity will ultimately determine the fate of the expansion, and gravity is dependent upon the mass of the universe; specifically, there is a critical density of mass in the universe of 10^{-29} g/cm^3 (equivalent to a few hydrogen atoms in a phone booth) that determines what might happen.

If actual mass density is greater than critical mass density, the universe will expand, slow, stop and collapse back on itself into a "big crunch." This is a closed Universe. For a critical or flat universe the actual mass density equals critical mass density and the Universe will continue to expand forever, but the rate of expansion will slow more and more as time progresses. Everything in the universe will eventually become cold. If actual mass density is less than critical mass density, the universe will continue to expand with no change in its rate of expansion (the open Universe).

It is important to know how much dark matter exists in the universe. However, recent observations of the motions of distant supernovae suggest that the universe's rate of expansion is actually accelerating. This opens up a fourth possibility, an accelerating universe, in which the all galaxies will move away from each other relatively rapidly and the universe will become cold and dark (faster than in the open universe, but still on the order of tens of billions of years). What causes this acceleration is unknown, but it has been called dark energy.

Astronomical observations can answer all such questions, or at least provide some guidance. Hopefully, in the next decade, we will know if the stable CDM WIMP dark matter theory is true or untrue. Just because WIMPs are beautiful dark-matter candidates does not mean that dark matter must consist of WIMPs. We all hope that we will soon be in an era of abundant data when all the unsolved puzzles will be answered. The key will be to see how all these different searches fit together to present a unified picture of the nature of Universe.

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