DARK MATTER AND NEUTRINOS

Gazal Sharma[1], Anu[2] and B. C. Chauhan[3]

Department of Physics & Astronomical Science
School of Physical & Material Sciences
Central University of Himachal Pradesh (CUHP)
Dharamshala, Kangra (HP) INDIA-176215.
[1]gazzal.sharma555@gmail.com [2]3anoman7@gmail.com
[3]chauhan@associate.iucaa.in

(submitted 03-08-2015)

Abstract

The Keplerian distribution of velocities is not observed in the rotation of large scale structures, such as found in the rotation of spiral galaxies. The deviation from Keplerian distribution provides compelling evidence of the presence of non-luminous matter i.e. called dark matter. There are several astrophysical motivations for investigating the dark matter in and around the galaxy as halo. In this work we address various theoretical and experimental indications pointing towards the existence of this unknown form of matter. Amongst its constituents neutrino is one of the most prospective candidates. We know the neutrinos oscillate and have tiny masses, but there are also signatures for existence of heavy and light sterile neutrinos and possibility of their mixing. Altogether, the role of neutrinos is of great interests in cosmology and understanding dark matter.

1 Introduction

As a human being the biggest surprise for us was, that the Universe in which we live in is mostly dark. The NASA's Plank Mission revealed in 2013 that our Universe contains 68.3% of dark energy, 26.8% of dark matter, and only 4.9% of the Universe is known matter which includes all the stars, planetary systems, galaxies, and interstellar gas etc.. This raises a number of questions in our minds; e.g. how much and how well we know about our Universe? What are dark matter and dark energy? What are they made up of? The very first suggestion of dark matter in our galaxy was made by Kapteyn and Jeans in 1922 and then by Lindblad in 1926. They proposed the existence of dark matter while observing the motions of nearby stars at right angle to the plane of our Milky way galaxy. Oort in 1932 claimed that there exists substantial amount of dark matter near the sun by observing the vertical motions of stars. However, in 1991, Kuijken and Gilmore argued that there were no significant evidence for dark matter with in the galactic disk near the sun.

Sinclair Smith and Fritz Zwicky in 1933, studied the large clusters of galaxies and found that galaxies were on average moving too fast for the cluster to be held together only by the mass of the visible matter. They concluded that in rich clusters of galaxies, a large portion of the matter is not visible i.e. the dark matter. The idea of dark matter in galactic halo was given by Freeman in 1970, while studying the rotation curve for NGC 300 and M33 by using the 21cm-Line of neutral hydrogen did not show the expected Keplerian decline beyond the optical radii. Then in 1979, Vera Rubin proposed that normal spiral galaxies contain substantial amount of dark matter present at great distances from the central regions. An influential model was proposed by Caldwell and Ostriker in 1981 for the density of core-halo type model of dark matter. The halo model is valid till now but the exact distribution of dark matter is still a mystery.

The next question to be addressed is about the constituents of dark matter. One of the biggest discoveries made by Hubble Space Telescope (HST) of NASA was the confirmation of invisible matter in the Universe. A 3D map of dark matter was derived from largest survey of the Universe made by the HST, the Cosmic Evolution Survey (COSMOS). The COSMOS survey covers a sufficiently wide area of sky - nine times the area of the full Moon (1.6 square degrees) - for the large-scale filamentary structure of an invisible form of matter that makes up most of the mass of Universe i.e. dark matter to be clearly evident [1]. The theory of Big-Bang nucleosynthesis (BBN), i.e. formation of light nuclei just after Big-Bang, as well as experimental evidences from anisotropies in Cosmic Microwave Background Radiation (CMBR) observed by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) indicate that most of the dark matter stuff is non-baryonic (which is not made up of regular matter).

Many experiments has been performed in search of dark matter candidates. Neutrinos, which are electrically neutral and tiny particles, seem potential candidates for dark matter, as they are long-lived and almost non-interacting with other particles. However, the three known types of neutrinos, called active neutrinos, are not massive enough to account for all of the dark matter of Universe. So, theorists proposed another type of neutrinos that would not interact at all with the regular matter, but are massive. If the sterile neutrino is heavy enough about $\sim 10\ keV$, it could account for the substantial amount of dark matter. The present article aims to introduce reader about the dark matter, its evidences, possible constituents and the potential candidature of neutrinos in the composition of dark matter.

2 Dark Matter

As discussed above the dark matter is the matter, which does not interact with light at all or may interact very poorly that it remains dark and unseen. As such, a question arises in ones mind; how one can detect something which does not interact with light. The answer may be 'gravity'; such that there are many astrophysical motivations for the detection of dark matter. There have been obtained a number of observational evidences for the existence of dark matter because of its gravitational effects, like galactic rotation curves of galaxies measured by Vera Rubin, confinement of hot gas in the galaxies, measurement on the basis of gravitational lensing [2], etc...

2.1 Flattened Orbital Velocity Curves

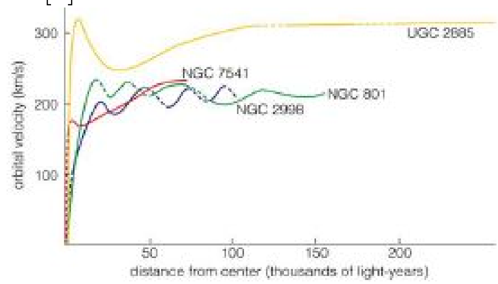
Before describing observations let us see how celestial objects respond to the gravitational force acting on them and how that response can reveal the large scale distribution of matter. For the planets in orbit around the sun which embodies essentially all the mass of the solar system, the decrease in gravitational attraction with distance is given by Newton law of gravitation. It has been found that orbital velocities of planets decreases with distance from the centre of the sun. In spiral galaxy the gas, dust and stars in the disk of the galaxy all orbit around a common centre. Like planets in solar system, the gas and stars move in response to the combined gravitational attraction of all other mass. If the galaxy is visualized as a spheroid, we can calculate the gravitational attraction due to mass M_r lying between the centre and an object of mass m in an equatorial orbit at a distance r from the centre. If the galaxy is neither contracting nor expanding then the gravitational force is exactly equal to the centrifugal force on the mass at distance r is given by the equation

$$GmM_r/r^2 = mv_r^2/r, \tag{1}$$

where v_r is the orbital velocity. When the equation is solved for v_r , the value of m drops out and the velocity of a body at a distance r from the centre is determined only by the mass M_r inward from its position. In the solar system, virtually all the mass is concentrated near the centre and the orbital velocity decrease as $1/\sqrt{r}$, that is called Keplerian decline.

In a galaxy the brightness is strongly peaked near the centre and falls off rapidly with distance. As per the distribution of luminosity, it was expected that stars at increasing distance from the centre would have decreasing Keplerian orbital velocities. When the orbital velocity of different stars present at different distances in a galaxy was studied by Vera Rubin, the unexpected results came

Figure 1: *Variation of orbital velocity with radius* [3]



out. This observation has been made for different spiral galaxies like Sa, Sb, Sc etc... Although each galaxy exhibits distinctive feature in its rotational pattern, the systematic trends that emerge are impressive. With increasing luminosity galaxies are bigger, orbital velocities are higher and the velocity gradient across the nuclear bulge is steeper. Moreover, each type of galaxy displays characteristic rotational properties.

Therefore we can draw conclusion from our observation that all the rotation curves are either flat or rising out to the visible limits of the galaxy. There are no extensive regions where the velocities fall off with distance from the centre, as would be predicted if mass were centrally concentrated. The conclusion is inescapable- mass unlike luminosity is not concentrated near the centre of spiral galaxies. Thus the light distribution in a galaxy is not at all a guide to mass distribution. Instead the mass inside any given radial distance is increasing linearly with distance and contrary to what one might expect, is not converging to a limiting mass at the edge of the visible disk. The linear increase in mass with radius indicates that each successive shell of matter in the galaxy must contain just as much mass as every other shell of the same thickness. Since the volume V of each successive shell increases as the square of the radius, the density ρ of matter in successive shells must decrease in order to keep ρV constant [4].

The widely accepted idea about the dark matter is that each spiral galaxy is embedded into a halo of dark matter. The gravitational attraction of the unseen mass keeps the orbital velocities high at larger distance from galactic centre. Till now we are not able to find the exact distribution of dark matter but we can say that it is strongly clumped around the galaxies. The density of dark halo decreases with distance from galactic centre as given by Caldwell and Ostriker

$$\rho_d = \frac{\rho_0}{1 + \frac{r^2}{a^2}}. \qquad (2)$$

They found a fit for the data with $\rho_0 = 1.37 \times 10^{-2} M_{\odot} pc^{-3}$, and $a = 7.8 kpc$.

If we consider a different distribution for dark matter in which we put all the unseen matter in a disk, the disk will quickly become unstable. Therefore P. Ostriker and Peeble suggest that the halos are important for stabilizing the disk. Additional evidence on the high rotational velocity was provided by the 21-centimetre radio waves emitted by the neutral hydrogen in the galactic disk. From the above discussion we can draw a conclusion that the density of dark matter halo surrounding the visible matter decreases slowly outwards.

2.2 Gravitational lensing

According to Einstein's theory of general relativity large objects with their immense masses can distort space-time therefore large massive objects such as galaxy clusters bend light from distant sources, creating distorted images that we can see here on earth. This is called gravitational lensing. This technique is especially useful for detecting dark matter. Since dark matter doesn't interact with light, it can't be seen directly. However, since dark matter is very massive, it can be detected indirectly by the distorted images it creates of normal matter through gravitational lensing. By measuring the angle of bending, the mass of the gravitational lens can be calculated-greater the bend, more massive the lens is. Therefore the angle of deflection is given by [5]

$$\alpha = \frac{4GM}{c^2 b}, \tag{3}$$

where b is the impact parameter. Using this method, astronomers have confirmed that the galactic clusters indeed have high masses exceeding those measured by the luminous matter. There have been several positive reports on the observation of such microlensing, even though typically only one in a million stars examined is expected to show such an effect. The bending of light by a massive object, a general relativity effect has been verified to extreme accuracy (better than 1%) by studying radar echoes from the planets when they are in conjunction. Experiments like the Large Synoptic Survey Telescope (LSST), under construction in Chile, aim to take advantage of gravitational lensing to map the dark matter in the Universe and provide clues to its nature. MOA (Micro-lensing Observations in Astrophysics) is a Japan/NZ collaboration that makes observations on dark matter, extra-solar planets and stellar atmospheres using the gravitational micro-lensing technique at the Mt John Observatory in New Zealand. HST of NASA recently produces several images of gravitational lensed objects. Therefore finding enough gravitational lenses to constrain the properties of dark matter structures requires a powerful telescope with a huge field of view like LSST.

2.3 Fluctuations in CMBR

The Cosmic Microwave Background (CMB) is the earliest photograph of our Universe. The patterns that we see in observations of the CMB were set up by competition between two forces acting on matter; the force of gravity causing matter to fall inward and an outward pressure exerted by photons (or particles of light). This competition caused the photons and matter to oscillate into-and-out-of dense regions. If the Universe consisted partially of dark matter in addition to normal matter, that pattern would be affected dramatically. The existence of dark matter leaves a characteristic imprint on CMB observations, as it clumps into dense regions and contributes to the gravitational collapse of matter, but is unaffected by the pressure from photons. We can predict these oscillations in the CMB with and without dark matter, which often present in the form of a power spectrum.

The power spectrum of the CMB shows us the strength of photon-matter oscillations at different parts of sky. The Far-Infrared Absolute Spectrophotometer (FIRAS) instrument has measured the spectrum of the cosmic background radiation, making it the most precisely measured black body spectrum in nature. The Cosmic Background Explorer (COBE) was launched in 1989 in search of temperature anisotropies; frequency power spectrum; solar system and galactic dust foregrounds. The WMAP in 2010 was the first instrument to measure the CMB power spectrum through the first peak of oscillations, and showed that the existence of dark matter is favoured. Comparison of such calculations with the observations of CMB Radiation by Plank mission team in 2013 have shown that the total mass energy of the known Universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy. Thus dark Universe constitutes 95.1% of the total matter energy content of the Universe [6].

2.4 X- Ray Studies

The observational evidences from X- ray studies also supports the existence of dark matter. The basic technique is to estimate the temperature and density of the gas from the energy and flux of the X-rays using X-ray telescopes, which would further enable the mass of the galactic cluster to be derived. The measurements of hot gas pressure in galactic clusters by X-ray telescopes, such as CHANDRA X-ray observatory by NASA, have shown that the amount of superheated gas is not enough to account for the discrepancies in mass and that the visible matter approximately constitutes only $12-15\%$ of the mass of the cluster. Otherwise, there won't be sufficient gravity in the cluster to prevent the hot gas from escaping [6].

Recently in 2014, data came from the European Space Agency's (ESA's) XMM-Newton spacecraft, which was analysed by an international team of researchers. After scouring through thousands of signals, they spotted a weird spike in X-ray emissions coming from two different spots in the Universe: the Andromeda galaxy and the Perseus galaxy cluster. The signal doesn't correspond to any known particle or atom, and is unlikely to be the result of a measurement or instrument error hence it could have been produced by a dark matter particle. The signal's distribution within the galaxy corresponds exactly to what we expects with dark matter i.e. concentrated and intense in the centre of objects and weaker and diffuse on the edges. Scientists believe that there is a possibility that it could come from dark matter candidate i.e. possibly the hypothetical heavy sterile neutrinos; as it is believed the decay of these particles could produce X-rays [7].

3 Baryonic & Non-Baryonic Dark Matter

On the basis of observed orbital velocity curves, and other evidences we can say that dark matter exists. Baryonic dark matter is non-luminous matter in which most of the mass is attributed to baryons, most probably neutrons and protons. Candidates for baryonic dark matter include non-luminous gas, Massive Astrophysical Compact Halo Objects (MACHOs). These MACHOs may include condensed objects such as black holes, neutron stars, white dwarf, very faint stars, or non-luminous objects like planets and brown dwarfs. Baryonic dark matter cannot be detected by its emitted radiation because these objects have very low luminosity, but the presence of these objects can be inferred from their gravitational effects on visible matter [6].

The nucleosynthesis of the elements and observations of the Cosmic Microwave Background Radiations (CMBR) puts constraints on the density of baryonic matter. No more than 15% of the matter in the Universe can be baryonic but most of dark matter stuff is non-baryonic. Non-baryonic dark matter (NBDM) is non-luminous matter made from non-baryonic stuff (other than protons, neutrons etc.). Recent measurements of the matter density Ω^0_m and the energy density Ω^0_Λ comes from three types of observations: 1) supernova measurements of the recent expansion history of the Universe; 2) cosmic microwave background measurements of the degree of spatial flatness, and 3) measurements of the amount of matter in galaxy structures obtained through big galaxy redshift surveys agree with each other in a region around the best current values of the matter and energy densities $\Omega^0_m \simeq 0.27$ and $\Omega^0_\Lambda \simeq 0.73$. Where Ω is the energy density of Universe defined by

$$\Omega = \frac{\rho}{\rho_c}, \tag{4}$$

where ρ_c is the critical density (average density of Universe to halt its expansion) of the Universe and Ω^0 represents present energy density of Universe. Measurements of the baryon density in the Universe using CMBR spectrum and primordial nucleosynthesis (i.e. BBN) constrain the baryon density Ω^0_b to a value less than 0.05. The difference $\Omega^0_m - \Omega^0_b \simeq 0.22$ must be in form of non-baryonic dark matter [8]. The value of total matter density

$$\Omega^0_m h^2 = 0.135^{+0.008}_{-0.009}, \tag{5}$$

out of which the baryonic matter is

$$\Omega^0_b h^2 = 0.0224^{+0.0009}_{-0.0009}, \tag{6}$$

in the form of neutrinos

$$\Omega^0_\nu h^2 < 0.0076, \tag{7}$$

and the matter in the form of Cold Dark Matter (CDM) is

$$\Omega^0_{CDM} h^2 = 0.113^{+0.008}_{-0.009}. \tag{8}$$

The results of BBN that tell that $\Omega_B \sim 0.01$ and therefore if Ω total is truly unity, then the bulk of the mass of the Universe must be in the form of some sort of non-baryonic matter. From baryon to photon ratio i.e. $\eta = \eta_B/\eta_\gamma$, one can find the range for η as given by [20]

$$4.7 \times 10^{-10} \leq \eta \leq 6.5 \times 10^{-10}. \tag{9}$$

We can find relative baryon density Ω_B as

$$0.017 \leq \Omega_B^0 h^2 \leq 0.024. \qquad (10)$$

This shows that Universe is not closed by baryonic matter and this gives the indication of existence of dark matter. From the analysis of the existing data follows that

$$\Omega_{DM} \simeq 0.20. \qquad (11)$$

The non-baryonic dark matter is classified in terms of the mass of the particle that is assumed to make it up, and the typical velocity dispersion of those particles (since more massive particles move more slowly). There are three prominent hypotheses on non-baryonic dark matter, called Hot Dark Matter (HDM), Warm Dark Matter (WDM), and Cold Dark Matter (CDM); some combination of these is also possible. CDM is composed of substantially massive particles ($\sim GeV$) expected to be moving with non-relativistic speeds. The leading candidates for CDM called WIMPs (Weakly Interacting Massive Particles). WIMPs could include large number of exotic particles such as neutralinos, axions, photinos etc. These particles forms dark matter, because they have too much mass to move at high speeds and that they are the best candidates for dark matter. As WIMPs can interact through gravitational and weak forces only, they are extremely difficult to detect. There are several experiments setup for detection of WIMPs such as SuperCDMS, NASA's Fermi Gamma-Ray Space telescope, Large Hydron Collider (LHC) at Geneva etc... Experimental efforts to detect WIMPs include the search for products of WIMP annihilation, including gamma rays, neutrinos and cosmic rays in nearby galaxies and galaxy clusters; direct detection experiments designed to measure the collision of WIMPs with nuclei in the laboratory, as well as attempts to directly produce WIMPs in colliders, such as the LHC. However all the efforts in this direction has been fruitless so far.

The HDM consists of particles to be moving nearly at the speed of light, when the pre-galactic clumps began to form. HDM includes massive ($\sim eV$) neutrinos. The neutrinos are the only hot dark matter candidate as they are light enough to move with the speed of light. The Universe is full of neutrinos left over from just after the Big-Bang, when matter and anti-matter were formed. There are huge amount of neutrinos, that if they have just a tiny mass, then they can significantly account for the dark matter. The dark matter that has properties intermediate between those of hot dark matter and cold dark matter named as Warm Dark Matter (WDM). WDM is composed of sub-relativistic particles having masses ($\sim keV$) causing structure formation to occur bottom-up (micro to macro scale)from above their free-streaming scale, and top-down (macro to micro scale) below their free streaming scale. The most common WDM candidates are considered to be sterile neutrinos and gravitinos. The WIMPs when produced non-thermally could be candidates for WDM [9].

The most widely discussed models for non-baryonic dark matter is based on the CDM hypothesis. CDM leads to bottom-up formation of structure in the Universe i.e. small scale structures led to the formation of large scale structures. On the other hand, the HDM results in top-down formation scenario i.e. first super-cluster formed and then galaxies and then the formation of small structure takes place. However, WDM has intermediate role in large scale structure formation.

4 Neutrino Dark Matter

Neutrinos are most abundant particles in the Universe. They are electrically neutral and have tiny mass. Out of four interactions in nature neutrinos interact only via the weak interaction and feebly via gravitational force. They rarely interact with any material, which makes experimental detection of these particles extremely challenging. There are three types of neutrinos so far detected, which are denoted as electronic (ν_e), muonic (ν_μ), and tauonic (ν_τ) flavour eigenstates. In fact, in the Standard Model of particle physics, neutrinos are massless. However, in the late 90's and beginning of 21^{st} century, physicists observed neutrino oscillation, a quantum mechanical effect which would not occur unless neutrinos have mass. The theory of neutrino oscillation describes the flavor eigenstates as the mixing or linear superposition of mass eigenstates ν_1, ν_2, ν_3. For two flavour case the mixing is shown as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}, \tag{12}$$

where θ is a mixing angle. From the observation of the neutrino oscillations phenomenon, it is confirmed that neutrinos have mass. The nature of neutrinos is not yet understood i.e. whether they are Dirac or Majorana particles. In case of Dirac nature neutrino and antineutrino are different, while in the Majorana nature they are the same particle. Despite the tininess, the neutrino mass has far-reaching implications in astrophysics and cosmology.

Neutrinos are considered to be the constituent of dark matter via thermal mechanism. As discussed above the hot dark matter is the matter that was relativistic until just before the epoch of galaxy formation, neutrinos of very low mass are strongest candidates for hot dark matter. It is believed that neutrinos were in thermal equilibrium with the hot plasma which filled the early Universe. As the Universe expanded and cooled, the rates of weak interaction processes decreases and neutrino decoupled when these rates became smaller than the Hubble expansion rate. Since for the three known light neutrinos with masses smaller than $1eV$, the decoupling occurred when they were relativistic called hot relics. As their interaction of cross section with matter is very small therefore, the direct detection of these relativistic neutrinos is an extremely difficult task. In early Universe, when $1MeV \leq T_\gamma \leq 100MeV$, neutrinos were kept in equilibrium with primordial plasma by the weak interactions. The reactions of neutrinos with nucleons were negligible, because the number density of the non-relativistic nucleons was much smaller than the density of relativistic electrons and positrons. The interaction rate for each neutrino is given by[13]

$$\Gamma \ = n < \sigma v >, \tag{13}$$

where n is the number density of target particles, σ is the cross-section and v is the neutrino velocity. The bracket denote the thermal averaging. For weak interaction processes

$$< \sigma v > = G_F^2 T_\gamma^2, \tag{14}$$

where the temperature (T_γ) gives the order of magnitude of the energies of the relativistic particles participating in the reactions. As the number density of relativistic particles is given as $n \sim T_\gamma^3$, the interaction rate for each neutrino became

$$\Gamma \sim G_F^2 T_\gamma^5. \tag{15}$$

So we can say that interaction rate decreases rapidly with the decrease of the temperature due to expansion of the Universe and we obtain the decoupling temperature for neutrinos $T_\gamma^\nu \sim 1MeV$.

If the active neutrinos have a non-zero mass, as indicated by several neutrino oscillation experiments, the sterile neutrinos will take part in the neutrino oscillations. The sterile neutrinos are 'sterile' as they practically inactive, and they don't interact via any other interactions with active neutrino except by mixing [21]. This allows a possibility for a radiative decay under emission of an X-ray photon with energy of half the sterile neutrino mass. However, it needs much more confirmation before one accepts this as the explanation.

The sterile neutrino was originally proposed as a dark matter candidate by Dodelson and Widrow in 1993 to solve the discrepancies between the CDM predicted structure formation and observations [20]. Since neutrinos were relativistic at the time of decoupling, the number density of relic neutrinos is given by the relativistic expression independent from the values of their masses. In other words, light neutrinos are hot relics and contribute to the hot dark matter in the Universe. Sterile neutrinos have been invoked to generate masses for light neutrinos; as such the mix with light neutrinos and hence can be produced via oscillations [20]. With this mechanism, their relic density is estimated to be

$$\Omega_N \approx \left(\frac{\sin^2\theta}{3\times 10^{-9}}\right)\left(\frac{M_N}{3keV}\right)^{1.8}. \tag{16}$$

Here, θ is the mixing angle between the sterile neutrinos N with mass M_N and the active neutrinos. It has been seen that a viable sterile neutrino to be the dark matter candidate requires a mass of keV and a very small mixing angle. It is a WDM candidate and its interactions are dominated by gravity, as preferred by the structure formation [22].

Neutrinos with masses much smaller than the effective neutrino temperature are still relativistic and have negligible contribution toward the energy density of the Universe. Despite the second most abundant particles after the photons, neutrinos fail to accommodate the observed abundance of dark matter. The relic density of light neutrinos is fixed as

[13]

$$\Omega_\nu^0 h^2 = \frac{\sum_i m_i}{94.14eV}. \quad (17)$$

Thus, the neutrino energy density is proportional to the sum of neutrino masses. This value is relevant for the present energy balance if there are neutrinos with masses of the order of $1eV$ or more. Before the neutrino decoupling around $T_\gamma \simeq 1MeV$, the weak processes were in equilibrium.

$\Omega > 1$, implies a closed Universe, which means that at some time the gravitation attraction will stop the expansion and Universe will collapse again. An $\Omega < 1$, means a Universe which expands forever. However $\Omega = 1$ means a flat Universe. At present time, Ω is changing on time scale of seconds. Since our existence is not compatible with the Universe which is either closed or continuously expanding, the only long term value that Ω is close to unity. Although the detailed physical mechanism for driving the expansion is not well determined and differs in different grand unified theories.

The phenomenon of sudden and fast expansion of Universe caused by a scalar field present in the nascent stage is known as 'inflation'. Inflation provides a possible mechanism to set the initial conditions. From the inflation paradigm, it is the argument that the only long lived natural value for Ω is unity and that inflation provided the early Universe with the mechanism to achieve that value and thereby solve some of the main problems of standard model of cosmology; e.g. the flatness and smoothness problems.

The WMAP-7 data provides a quite stringent constraint on the sum of neutrino masses of $\sum m_\nu < 1.3\ eV$ at 95% c.l. [10], which is more constrained than $\approx 2.1eV$, that is the first releases [11]. However, the most recent and sophisticated analysis of Lyman-a data gives an upper bound of 0.9 eV for the sum of neutrino masses. In summary, at present the bound on the sum of neutrino masses can be in the range between 0.3 and more than 2 eV, depending on the data and parameters used. The bound can be relaxed somewhat when more parameters, such as sterile neutrinos (ν_s) are included. In the most conservative case the bound is above 2.5 eV if only CMB data is used. When CMB data is combined with LSS data in the linear or almost linear regime, combined with a prior on the Hubble parameter the upper bound is robustly below 1 eV. This is true even for extended models. Here it should perhaps also be noted that the bound on neutrino mass from cosmic structure formation applies to any other, hypothetical particle species which decouples while still relativistic. This could for example be low mass sterile neutrinos. It could also be relatively high mass axions which decouple after the QCD phase transition.

Neutrinos have a kinematical advantages over the dark matter candidates is that they cluster on large scales, where the dark matter is needed to hold the large clusters of galaxies. In HDM, since they decoupled at a temperature of the order of $1MeV$ when they were relativistic and formed relativistic HDM gas. The HDM perturbations within the horizon are erased by free streaming (i.e. the random particle velocities close to the velocity of light disperse all HDM over-densities). Free streaming ceases when the HDM gas becomes non-relativistic at some red-shift Z_{nr}. Thus, only the HDM perturbations with wavelength larger than the horizon distance at Z_{nr} survive and can take part in the generation of structure in the Universe. Since the horizon distance at Z_{nr} is typically much larger than the volume corresponding to the galactic size masses, so in a Universe dominated by HDM, the formation of structures must proceed according to top-down mechanism. However the observed statistical properties favours bottom-up mechanism i.e. small structures leading to the formation of large scale structures. Hence the HDM contribute to the formation of small scale structures while CDM is responsible for binding of large scale structures [13].

The standard model does not predict any masses for the active neutrinos, but as stated above the masses are required by the experimentally verified neutrino oscillations. A simple way to incorporate the neutrino masses is to extend the model with the right-handed neutrinos just as done for the other elementary particles of SM. It is possible to add an arbitrary number of sterile neutrinos, but at least three sterile neutrinos are needed to explain the neutrino oscillations, the baryon asymmetry, and the dark matter [14]. The successful 'three sterile neutrinos' extension of the standard model is called the (Neutrino Minimal Standard Model)(νMSM). It is re-normalisable and in agreement with most particle physics experiments [15]. The Big-Bang production of ^4He increases with η. Thus upper limit to ^4He abundance and a lower limit to baryon density lead to an upper limit to number of neutrino species N_ν (i.e. so called BBN bound). The lower limit to baryon density is based on the Big-Bang production of deuterium ^2H, which rises rapidly with decreasing baryon density. Since all the neutrons end up in forming ^4He, which is the most tightly bound stable light nucleus, the mass fraction of ^4He is denoted as Y_p, and is given by [13]

$$Y_p \simeq \left(\frac{2n_n}{n_n + n_p}\right) \simeq 0.25. \tag{18}$$

As per recent estimates of Y_p with conservative assumptions - for ^3He chemical evolution and $Y_p = 0.252$, less than four neutrino species are possible; however, for extreme assumption- no limit to primeval deuterium- less than five neutrino species are allowed which implies there exist fourth neutrino flavor that is sterile neutrino. In summary, there are healthy signatures for additional degrees of freedom $N_\nu > 3$ i.e. the species of sterile neutrinos from various studies, which are given below [16]: $2.98 < N_\nu < 4.48$ [BBN](68% CL); $3.03 < N_\nu < 7.59$ [WMAP5+SDSS-DR7+Ho] (95% C.L.); $3.46 < N_\nu < 5.20$ [WMAP7+BAO+New Ho](68% CL); $4.0 < N_\nu < 6.6$ [WMAP7+ACT data](68% C.L.); $2.22 < N_\nu < 9.66$ [WMAP3](68% CL).

Using recombination-era observables including the CMB, the shift parameter RCMB and the sound horizon from Baryon Acoustic Oscillations (BAO) severely constrain the sterile neutrino $\sin 2\theta < 0.026(m_s/eV)^-2$.[17]. Recent bounds on the mixing between the active and the sterile neutrinos have been derived from the combination of neutrino oscillation data and direct experimental searches for sterile neutrinos.[18] Electron neutrino-sterile neutrino mixing bound [19] from joint fits of solar, KamLAND, Daya-Bay and Reno experiments is $\sin 2\theta_{es} < 0.2$. and the analysis of cosmological data in terms of ΛCDM constrains the mass square difference with one sterile family $\Delta m^2_{41} < 0.25eV^2$.

5 Conclusions

Ever-since the dawn of civilisation man has been fascinated by the stars, planets and other heavenly objects, wondering what essentially the magnificent Universe was made up of. We learnt that our Universe is almost completely dark. To understand this mystery was the main thrust to know more about the invisible Universe. The story of dark matter began nearly a century ago, when Kapteyn and Jeans propounded of existing a such kind of weird matter. Later, Smith and Zwicky discovered that in some large clusters of galaxies the individual members are moving so rapidly that their mutual gravitational attraction is insufficient to keep the clusters from flying apart. Either such clusters should be dissolving or there must be enough dark matter present to hold them together. Since, almost all the evidences suggest that clusters of galaxies are stable configuration. Hence it was concluded that the clusters consist of both luminous and non-luminous matter, which was termed as dark matter.

In this paper we have discussed about the dark matter, various experimental hints and evidences for dark matter, its composition, the role of neutrinos in dark matter formation and understanding of its dynamics. Baryon to photon ratio shows that our Universe is not closed by baryonic matter, which gives a clear indication of the existence of dark matter. Given the properties, neutrinos fit to be a strong candidate constituent for the dark matter as they have an advantage over other dark matter candidates, e.g. they cluster on large scale where the dark matter is needed to hold the large clusters of galaxies. Despite the weakness of interactions and smallness of masses, they can play an important role in cosmology.

In addition to three active flavours of neutrinos, there could also exist extra massive neutrino states that are sterile, i.e. they are singlets of the Standard Model gauge group and thus insensitive to weak interactions. Most of the current data on neutrino oscillations can perfectly be explained with only three active species, but there exist a few experimental results [23]-[28] that cannot be explained in this framework. If neutrino oscillations are responsible for all the experimental data, a solution might require additional (sterile) neutrino species. These kind of particles are predicted by many theoretical models beyond the SM [29]. Their masses are usually heavy, while lighter sterile neutrinos are rarer but possible. Recent studies propose sterile neutrino with a mass of the order of a few keV's and a very small mixing with the active neutrinos. Such heavy neutrinos could be produced by active-sterile oscillations but not fully thermalized, so that they could play the role of dark matter and replace the usual CDM component. But due to their large thermal velocity (smaller than that of active neutrinos), they would behave as WDM and erase small-scale cosmological structures. At present the neutrino physics and neutrino astrophysics and cosmology are at the cross roads. On the one hand, it is impossible to deny that neutrinos oscillate and thus presumably have small masses, and on the other unless a sterile neutrino truly exists, there is a sense that neutrino masses are too small to be of very much cosmological interests.

In the galaxy formation scenario, galaxies can only form by the collapse of superclusters. The detailed study shows that the collapse of super-clusters only happens very late and may be in contradiction with the existence of quasars of large red shift. Although the evidences for dark matter is wide and deep and existence of dark matter is based on the assumption that the laws of motion and gravity as formulated by Newton and extended by Einstein apply. On the other hand the modification in the theory of gravity can explain the effects attributed to dark matter and some scientists have proposed MOND (Modified Newtonian Dynamics). According to this theory at very low acceleration, corresponding to large distances, the usual law of gravitation is modified. Although MOND has had some success in explaining observations of galaxies, but failed to explain the observation of Bullet Clusters. So we need more experimental evidences to give a conclusive theory of dark matter.

Acknowledgments

We thank Debasish Majumdar, SINP, for giving useful inputs. The Inter-University Centre for Astronomy & Astrophysics (IUCAA), Pune is also acknowledged for providing research facilities during the completion of this work.

References

[1] Massey, R. et al., Dark matter maps reveal cosmic scaffolding, doi:10.1038/nature05497, 7 January 2007 as the related references.

[2] E. Copeland, *Dark Matter in the Universe*, Contemporary Physics, 35(1), 1994.

[3] www.google.co.in/imghp [image taken from google].

[4] V. Rubin, *Dark Matter in Spiral Galaxies*, Sc. Am. 248(6), 1983.

[5] A.C. Melissinos, Lecture Notes on Particle Astrophysics, Physics 593- Spring 1995.

[6] S. Sharma, *Bulletin of the Indian Association Of Physics Teachers*, 6(9), 2014.

[7] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, *Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster*, Phys. Rev. Lett. 113, 251301, 2014.

[8] P. Gondolo, *Introduction to Non-Baryonic Dark Matter*, Lecture delivered at the NATO Advanced Study Institute, France [astro-ph/0403064].

[9] S. R. Sorensen, *Sterile neutrinos as a dark matter candidate*, Master Thesis in Physics, Niels Bohr Institute, Dark Cosmology Centre, August 25, 2006.

[10] E. Komatsu et al., *Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation*, WMAP Collaboration, Astrophys.J.Suppl. 192 18 (2011).

[11] K. Ichikawa, M. Fukugita and M. Kawasaki, Phys. Rev. D 71, 043001 (2005).

[12] S. Dodelson and L. M. Widrow, *Sterile-neutrinos as dark matter*, Phys. Rev. Lett. 72 (1994) 17?20.

[13] C. Giunti, C. W. Kim, *Fundamental of Neutrino Physics and Astrophysics*, Oxford University Press, New York, 2007.

[14] T. Asaka and M. Shaposhnikov, , Phys. Lett. B 620, 17, 2005.

[15] T. Araki and Y. F. Li, Q_6 *Flavour Symetry Model for the Extension of the MSM by the three Right Handed Sterile Neutrinos*, Phys. Rev. D85, 065016, 2012.

[16] P. C. de Holanda and A. Yu. Smirnov, hep-ph/1012.5627 [references contained therein].

[17] A. C. Vincent, E. Fernandez Martinez, P. Hernandez, M. Lattanzi, O. Mena, JCAP 04 (2015)006.

[18] O. Ruchayskiy, A. Ivashko, JHEP 1206 (2012) 100.

[19] A. Yu. Samirnov, Nucl. Phys. Proc. Suppl. 235, 431 (2013) [references contained therein].

[20] S. Bilenky, *Introduction to the Physics of Massive and Mixed Neutrinos*, Springer, Lecture Notes in Physics, 817, 2010.

[21] Signe Riemer-Srensen, *Sterile neutrinos as a dark matter candidate*, Master Thesis in Physics Niels Bohr Institute, 2006.

[22] C. J. Copi, D. N. Schramm, and M. S. Turner, *Big-bang Nucleosynthesis limit to the number of neutrino species*, Phys. Rev. D 55, 3389, 1997.

[23] A. Aguilar-Arevalo, *et al.*, (LSND Collaboration), *Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam*, Phys.Rev. D 64, 112007, 2001.

[24] A. Aguilar-Arevalo, *et al.*, (MiniBooNE Collaboration), Phys, Rev, Lett. 102, 101802, 2009.

[25] A. Aguilar-Arevalo, *et al.*, (MiniBooNE Collaboration), Phys. Rev. Lett. 110, 161801, 2013.

[26] G. Mention *et al.*, Phys. Rev. D 83, 073006, 2011.

[27] T. Mueller *et al.*, Phys. Rev. C 83, 054615, 2011.

[28] D. Frekers *et al.*, Phys. Lett. B 706, 134, 2011.

[29] S. Antusch *et al.*, *Unitarity of the Leptonic Mixing Matrix*, JHEP 0610, 084, 2006.

[30] D. O. Caldwell, *Neutrino Dark Matter*, University of California, Santa Barbara, CA 93106-9530, USA, hep-ph/9902219.

[31] G. G. Raffelt, *Neutrino Astrophysics At The cross roads*, Proc. of Summer School in High Energy Physics & Cosmology at ICTP Italy, World Sc., 1998 [hep-ph/9902271].

[32] K. Zuber, *Neutrino Physics*, CRC Press, first edition, 2013.