The Cosmic Dark Matter-A Riddle of Nature

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1.Dark Matter: Why and What?

The fate of the universe depends on its early past history. The knowledge of its components and amount of matter and energy present in the universe, are important and can be determined by the so-called ***density parameter*** $\boldsymbol{\Omega_o}$ at present time. The more precisely one can determine the value of Ω_o, the more accurately we know the fate of the universe. We have many reasons to believe that there might be extra matter present in the universe.

The studies of the distribution of luminous matter in the universe, especially in galaxies, appear that matter density seems to be ~ 10^{-30} g cm^{-3} which gives Ω_o about 0.1. The peculiar things arise from the attempt to match the observations with theory. The pioneering work by *Fritz Zwicky* and *Vera Rubin* showed that there is not much enough mass of the stars to hold galaxies into galaxy cluster. This assumption needs Ω_o to be at least 0.3 i.e. needs more matter than only the matter of visible objects. Also, in the calculation of galaxy rotational curve velocity we need more mass to contribute to the gravitational pull in the distant curve part (from centre of galaxy) of galaxy in order to maintain the rotational velocity of the curve as it was observed. Figure 1 presents the observational data (upper dark dots) compared to the velocity as it should be (predicted from theory) of galactic disk, gas and also the impossible halo which will be discussed later. The other supports are that the dynamic bulk motion of the universe also suggests the value of Ω_o to be at least 0.3, and the important problem comes from the ***flatness problem*** of cosmology which conjectures that the value of Ω_o is close to 1. This leads to the theory of ***inflationary universe*** proposed by *Alan Guth* in 1981.

These above evidences suggest that there should be other dominant components of the mass distribution in the universe that could not be detected by only observing visible objects, and this new matter itself exerts gravity. The kinds of these objects are collectively known as dark matter (DM) which is supposed to be the known objects or new unknown objects e.g., particle-like objects or larger compacted objects. There are many candidates for DM such as ***brown dwarf stars*** which are thought to be very faint to be observed visibly, ***neutrinos***, ***baryons*** (neutrons and protons (electrons are not baryons but the word "baryonic matter" includes electrons here)), ***black holes***, ***MACHOs*** (MAssive Compact Halo Objects) or even things we have not known them yet. The most likely candidate for these non-baryonic particles are the so-called Weakly Interacting Massive Particles (***WIMPs***). Neutrinos are thought to be in type of WIMPs particles. Figure 2 shows the rough conclusion of ranges of Ω_o value from various predictions compared to the logarithmic distant scale.

2. Baryonic and Non-Baryonic Dark Matter

2.1 Baryonic Dark Matter

Baryons can exert gravitational interaction, which is the crucial property for detection or modelling. Most of baryonic dark matter is thought to be the type of low mass stars with are called brown dwarfs. This type of stars occupies mass lower or equal to 0.08±0.01 of the solar mass ($M_\odot$) which can not generate nuclear fusion reaction. Then brown dwarfs are invisible.

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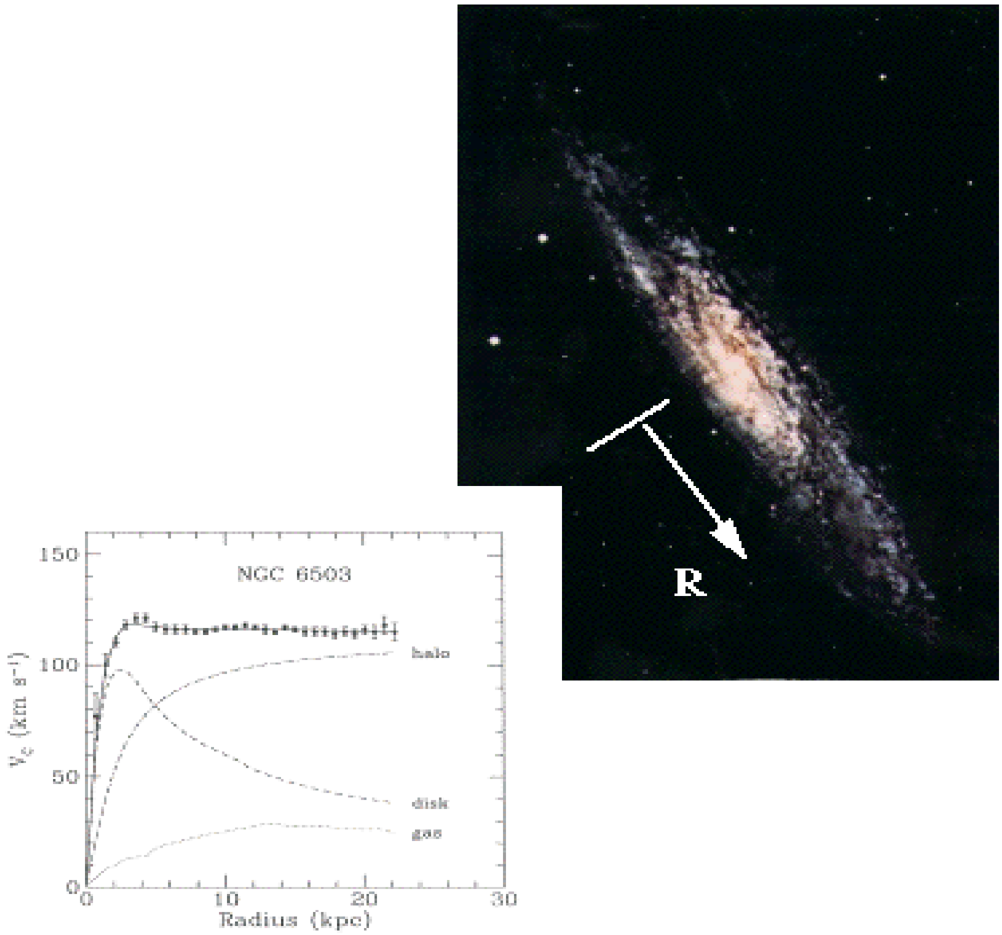

Figure 1: Variation of the velocity of galactic matter versus radius distance from galactic centre.

The search for these objects is very difficult because brown dwarfs are faint with lower temperature. Objects with surface temperatures between 1000 and 2000 K have unprecise spectra which are affected by board molecular absorption bands. They are very hard to construct the model (*Burrows A.*,& *Liebert J.*(1993)). From the theory of stellar formations, brown dwarfs or other low mass objects can be formed only by ***fragmentation***. By this way first the massive object collapses until its density is high enough that smaller internal clumps can grow. But this event is quite obscure to know how difficult or easily it could happen. The other clumps of low mass baryonic DM are planets (including us!) but they are too small masses in this scale to be significant.

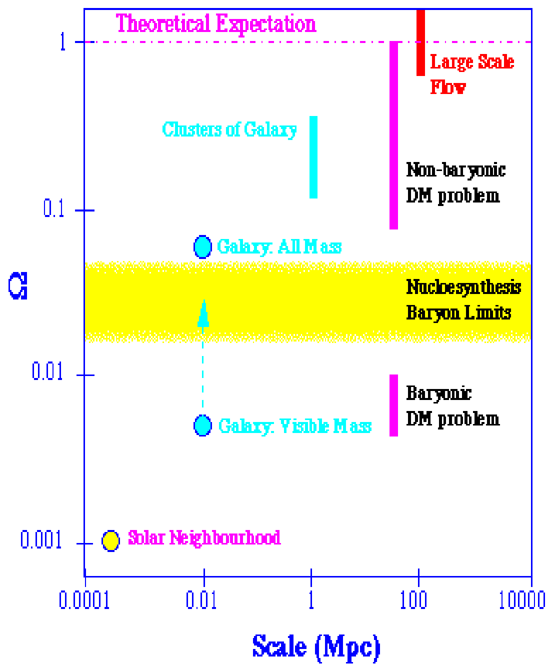

Figure 2: Ranges of Ω_o value from various predictions.

There are possibilities of existing some low mass baryonic dark matter near the sun or even other stars. This suggestion comes from uncertainty of mass-luminousity relation. When the low-mass part of the mass function remains weakly constrained even near the sun, at some distances gravitational dynamics require large amounts of dark matter. ***Gravitational microlensing*** results give the possible contribution of low-mass object but now they are confusing because microlensing bases on assumption that half of dynamic mass of the Milky Way is in the form of discrete objects with mass about $0.5M_{\odot}$. and it appears that these objects must take part not more than 20% level rather than dominant fragment of dark matter. Until now there are low interests in low-mass baryonic DM because there are quite low mass in this scale to find and to contribute.

The baryonic DM which may be interesting, should be around 1000th of or more than Jupiter-size for every solar mass stars. The two most possibilities of DM are diffused gas and dark stars (white dwarfs, neutron stars, black holes or other objects with mass around limit of burning). Search for baryonic DM in the form of MACHOs is active now with the observation of possible microlensing effect thought to be produced by MACHOs. The stars in LMC (Large Magellanic Cloud) are the interesting points. Result from this observation indicates that MACHOs could be significant part of ***dark halo*** (Figure 3) in which our galaxy is believed to locate inside. The earlier results show that MACHOs mass could be up to 50% of total halo mass. The mass left in halo is believed to be brown dwarfs, which is still obscure. Anyway, the recent researches by *Persic* and *Salucci* in 1992, numerical simulation by *Rauch* in 1997 and *Ostriker* in 1999, suggest that most of the baryons should still be in gaseous form which means most of baryonic DM should be in the form of gas.

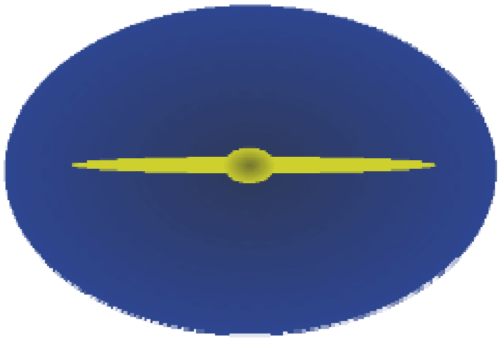

Figure 3: Dark halo.

2.2 Non-Baryonic Dark Matter

Non-baryonic DM could not exert gravitational attraction, and cosmological evidence suggests that DM should consist of weakly interacting particles.

Nucleosynthesis is the strongest support in its favour. Primordial nucleosynthesis estimates that baryonic contribution from density parameter should be

$$\Omega_B \sim 0.0125h^{-2}.$$

This value is the value when universe was about 1 second old with abundances of light elements. If we assume ***h*** (***Hubble constant***) to be 0.65 (quite high value of *h*), we will get $\Omega_B \sim 0.06$. Since the acceptable value for density parameter (Ω_M) of total matter in the universe is at least about 0.2, then the result can not be consensus with Ω_M. There should be (at least) another type of matter which is not baryonic. There are other important reasons which we think that most of DM in the universe should be non-baryonic. If the universe is dominated by baryons, the density perturbations for structure formations can not start until the time of ***decoupling*** (the time when atoms first were formed in the universe which was in the era of dust (particles) dominated universe (dust era)) and then stopped growing when curvature of the gravity dominates. Then the total growth of the cosmic structure is still very small compared to Ω_o=1 consistent with observations.

In WIMPs dominated universe this event can start as soon as the dust era starts. In the universe matter we know, are mainly baryons, photons, and three species of neutrinos (electron neutrinos, muon neutrinos and tau neutrinos) and may be other particles present in the ***standard model of particle physics***. There are several possible ways to explain what this non-baryonic DM could be. One idea is the neutrinos (neutrinos are particles in the standard model) which are light, neutral particle known to exist and contribute in big number in the early universe and at present time. There are approximately 100 neutrinos per cm^3 in the universe. One big problem for neutrinos is that their masses are still unknown. Other ideas are about the particles lying out of the standard model i.e. in the range of ***supersymmetric model*** (***SUSY***) or model we have not known?? Particles and various supersymmetric particles such as ***axion*** (mass $10^{-5\pm1}$eV) or ***neutralino*** (mass 50 GeV-500GeV). Mainly non-baryonic dark matter could be separated into two types; hot dark matter and cold dark matter:

2.2.1 Hot Dark Matter (HDM)

This matter are particles that occupy very small mass (of the order of a few eV is an archetype.) or massless, and move with the very high velocity. Neutrinos are the HDM candidate because neutrino mass is still uncertain whether massless or massive. Their number density roughly equals to that of photons ($n_\upsilon \sim 100\ cm^{-3}$). HDM decoulples when they were relativistic. Because they are massless, their mean energy is then

$$\langle E \rangle = \langle |p| \rangle c.$$

When universe expands these particles cool down and go nonrelativistic, and then their momentum and energy turn to be redshift. But their mean velocities are still very high. So we call this type of dark matter in the sense "hot". In neutrino-dominated universe an overdense fluctuation can not survive because neutrinos are very weakly interacting with all matter and also itself and they are collisionless. This phenomenon is called ***neutrinos free streaming***. The neutrinos free streaming can wipe out all perturbations if mass of neutrinos is less than the free streaming mass

$$M_{fs} = \rho_\upsilon (t_{fs}) V_{hor}(t_{fs}) = (M_P)^3/m_\upsilon^2 .$$

Because HDM model need massless neutrinos which surely have lower mass than M_{fs} .This leads to the conclusion that in the HDM-filled universe, formation of structures occurred in the "top-down" fashion i.e. the largest structures were formed first (because all smaller mass than M_{fs} scale must be suppressed), afterwards the smaller scale structures can be formed by fragmentation of the large structure (*White , Frenk,Davis* 1983). The other contrast for the existence of a bulk DM is from recent evidence from measuring atmospheric and solar neutrino mass in 1999 by *Totsuka, Kirsten* and *J.Bahcall*. This suggests tau neutrino mass at 0.1 eV, muon neutrino mass from 0.001 eV to 0.01 eV and electron with smaller mass. Before that in 1998, *Fukuda*'s research gave strong evidence for a neutrino mass different squared between two neutrinos of value around 0.01 eV^2 which can imply that neutrino mass is about 0.1 eV. If the above evidence is true, it could be believed that neutrinos are light and could be a good candidate in HDM. However, the "top-down" scenario is contradicted by the number of observations which indicate that larger structures were formed from many smaller structures - the "bottom-up" fashion (*Dodelson*, 1996).

2.2.2 Cold Dark Matter (CDM)

In contrast to HDM, CDM decouples when they are nonrelativistic. The number density is so high that their mass should be very large and the velocities should be nearly zero. This is the reason why we call this kind of DM "cold". This makes CDM concordant to the explanation of "bottom-up" fashion structure formation theory. In few years ago, the kinds of particles thought to be candidates of CDM are massive neutrinos and some massive particles from particle physics theory. Massive neutrino in this case is far from being the only candidate because they can close the universe with their mass and very recent results as stated in previous subsection, support light neutrinos. The particle theorists postulate two new possibilities. One is axion and the other is the Weakly Interacting Massive Particles or WIMPs which is the collective term for particles lying outside standard model. Cosmologists predicted that enough amounts of WIMPs necessary to account for the DM, could have been produced in big bang. WIMPs are predicted to be high mass particles, heavier than neutron, moving very slow and weakly interacting with other matters. Then WIMPs can be candidate for CDM.

In 1992, the first ***cosmic microwave background fluctuation*** was detected. Cosmic mirowave background (CMB) was created at decoupling time and was left until today with redshift. Fluctuation of CMB at that time could be caused from the structure formations, which create irregularities in temperature at matter lumps so far formed. CDM caused the formation of smaller structure in the fashion of "bottom-up" during decoupling phase. That is to say the idea of CMB anisotropy supports the idea of CDM in the view of structure formations. HDM can not be used to explain in this situation because HDM decoupled when they are relativistic particles.

3. Search for Dark Matter

3.1 Search for Baryonic DM

3.1.1 Gas

Since most of the baryons (matter we know) in clusters reside in hot x-ray emitting gas and do not reside in the galaxies, this problem has to employ on gas-to-total mass ratio. Gas mass could be measured by either measuring the x-ray flux from intracluster gas or mapping the Sunyaev-Zel'dovich (S-Z) cosmic microwave background radiation distortion effected by CMB photons which scatter off hot electrons in the intracluster gas. For the total cluster mass we have three methods. First method is by using dynamic motion of galaxy clusters and virial theorem. Second is by assuming hydrostatic equilibrium of gas and using this assumption to infer mass distribution. The third method by *Tyson* in 1999, is using results from gravitational lensing to map the cluster mass. By these procedures the mean matter density of the universe is summarised by *Turner* in 1999 with value $\Omega_M = 0.4 \pm 0.1$.

3.1.2 MACHOs and Brown Dwarfs

By surveying the stars in the LMC, one can look for by looking for possible microlensing effects due to MACHOs when they pass near the line of sight between the observer and stars. The results from Australian/U.S. collaboration "MACHO" experiments concludes that halo mass in form of MACHOs ,in the range 50 Mpc, could be up to 50% of total halo mass, and each MACHOs mass is between 0.5 to 1 $M_{\odot}$. Brown dwarfs may be candidates for DM in galactic halo, but the supporting observed information is weak (there are only eight microlensing events in all "MACHO" team and French "EROS" team). The very recent results from EROS collaboration suggest that not more than about 20% of dark matter in our galaxy is in the form of MACHOs.

3.2 Searching for WIMPs

This can be carried out from measurement of density and distribution of DM in our galaxy. About 10^{13} WIMPs are predicted to pass through every kilogram of matter on earth in every second, but only 1 WIMP particle per day per kilogram would interact with an atom by knocking an atom backwards. This recoiling atom will release energy when move and we expect to detect this energy. Detection is not so easy because there are many other particles in nature which would hit our detector. WIMPs detector must be in deep underground for preventing muon particles from comic ray and must be shielded to prevent other particles. In U.K., WIMPs project has the great site for installing WIMPs detector in deep salt mine at Boulby Mine in Yorkshire (Figure 4 and Figure 5).

Figure 4: Boulby Mine in Yorkshire.

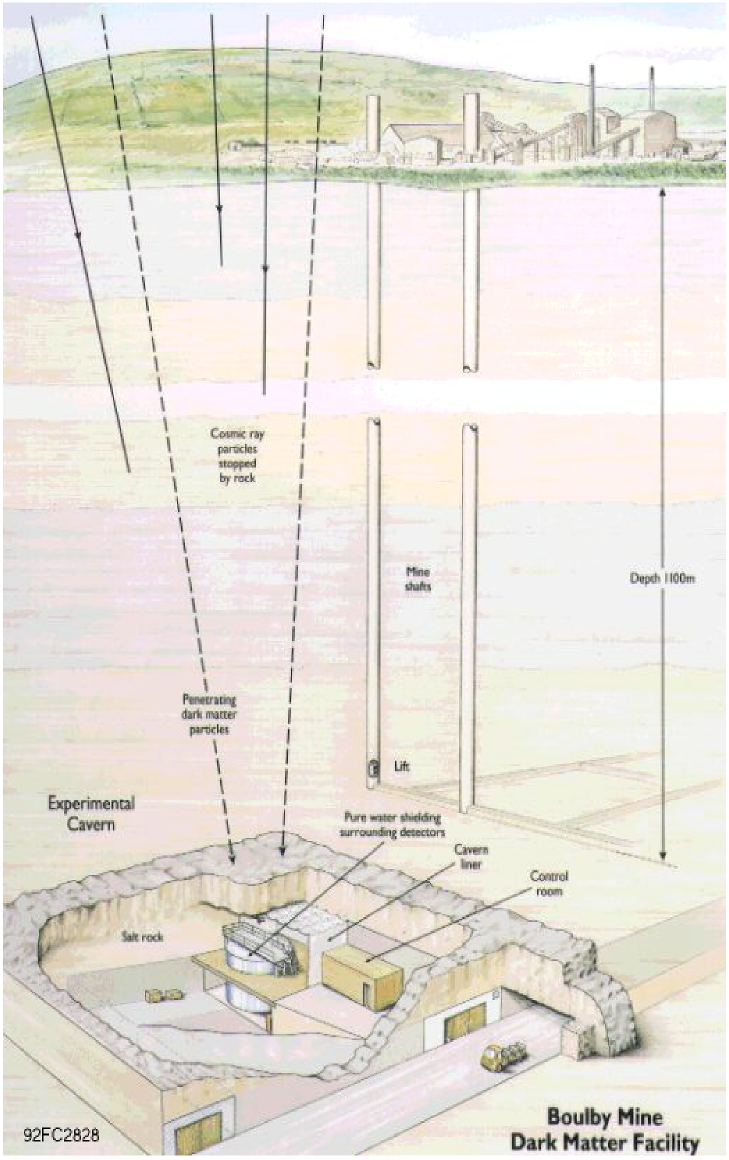

Figure 5: Dark Matter Facility at Boulby Mine.

4.Conclusion

The available evidences of DM are strong at present. DM type which may exist, are WIMPs, MACHOs, hot gas and smaller objects like brown dwarfs.

DM research area contributes to the question of the fate of the universe (close, flat or open universe) and also to the knowledge of Ω_o. All the things we suspect, are relevant to Ω_M value of universe which plays the central role, and it must be needed to match with nucleosynthesis problem and flatness problem. Particle physicists are now facing difficulties to do experiments at very high energy to confirm existence of exotic particles. In order to explain dark particles and the fate of the universe, we are now using the universe as our laboratory.

(All pictures presented in this article are taken from Sheffield University Particle Astrophysics Group 's web page. I would like to express my gratitude for editing to Dr. N. Nimai Singh, Department of Physics, Gauhati University, Guwahati, India, 781014.)

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