A survey on galactic dark matter

Deep Bhattacharjee [1], Sanjeevan Singha Roy [2], Ashis Kumar Behera [2], and Riddhima Sadhu [2]

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Abstract

This paper contributes an extensive analysis of Dark Matter (DM) along with associated materials regarding the interpretation of its evidence from 'cosmic microwave background radiation', 'gravitational lensing', 'galactic mergers and collisions', 'evolution and formation of galaxies', 'galactic clusters', 'Lambda-CDM models of the observable universe. Massive Astrophysical Compact Halo Objects (MACHOs), Weakly Interacting Massive Particles (WIMP's), Strongly Interacting Massive Particles (SIMPs), along with hot, warm, and cold DM, shedding an extensive overview of the γ_elastic of the cold DM after the chemical equilibrium is reached and kinetic decoupling happens earlier for γ_(in-elastic) accounting for 85% of the dominated matter in the universe. Scaler-Vector-Tensor (SVT) Gravity, MOdified Newtonian Dynamics (MONDs), and Gravity of Entropy (GoE) have emerged as a supplement of the modified General Relativity (GR) as a source of non-baryonic DM scenarios in the universe. Observable evidence has been taken into account for the 'dispersion of velocity', 'galactic rotation curves', 'Lyman-α forest simulations', '21 cm red-shift spectra', 'satellite sky surveys', 'formation of structures', and 'supernova measurements of Type Ia'. Direct evidence in the underground chamber for 'nuclear giggles' either 'Cryogenic experiments CRESST, CDMS' or 'noble liquid gases XENON' as a result of DM scattering via VECTOR-PORTALS and Indirect evidence as a result of sky-surveys like satellite telescopes ANTARES, AMANDA or through the 'collider experiments' in LHC, CERN, Geneva, Switzerland.

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Keywords and phrases: Astroparticle Physics, Dark Matter

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Introduction

The Einstein-Field equations described the 'dark energy as the cosmological constant or Λ' as follows,

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

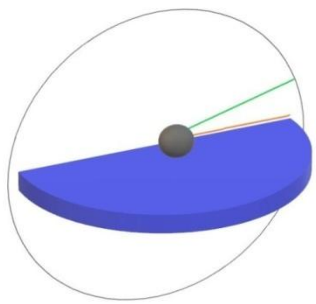

Fig. 1 The blue semi-circle represents the galactic disk with a radius (red line) of $\sim 10\ \mathrm{Kpc}$, width $\sim 0.5\ \mathrm{Kpc}$, the central (black sphere) is the black hole Sagittarius A* with a mass of $\sim 4 \times 10^6\ \mathrm{M}_\odot$ where the Sun is at a distance of $\sim 8.5\ \mathrm{Kpc}$ from the galactic centre and (Green line) represents the revolution function of the stars beyond the galactic disc to the DM Halo (black circle).

DM are invisible therefore, the traces that are left behind by the objects purports to the existence of DM and the interstellar medium comprises of ~10% of the total stellar mass providing evidence for the distribution of DMs. There are at least $\sim 10^{11}$ stars in the Milk Way where the collision between two stars takes $\sim 10^{21}$ years thereby proving that they are essentially collisionless. The time $\sim 10^{21}$ years is even greater than 13.8 * 10^9 billion years, the age of the universe, therefore something strange is acting between them[1,2,3,4].

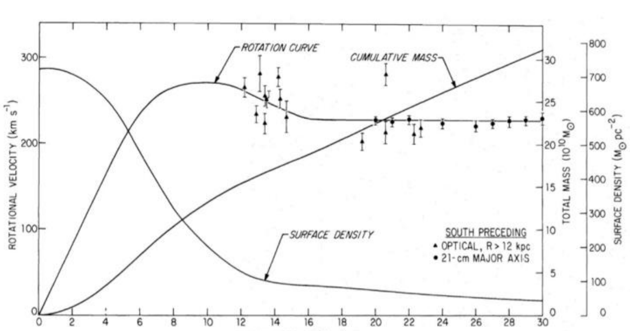

Fig. 2 The Andromeda galaxy (M31) rotation curve from Roberts and Whiteburst [5] shows after 13 Kpc, the curve instead of getting down, gets flattened at a region beyond the galactic disc.

Fig. 1 shows that at the (green line) beyond the galactic disc as a function of velocity which instead of dimi-

This $\Lambda + DM = 95\%$ of the content of mass-energy in the universe. The other constituents of 5% are of 'baryonic matter'. Dark-energy (Λ) constitutes 'negative pressure' which accelerates expansions.

nishing (upto the limit of red line) gets flattened out at $\sim 13\ \mathrm{Kpc}$ due to the presence of some invisible non-baryonic matters presented which interact only via gravitation but not electromagnetism and hence remains invisible as depicted in Fig. 2. Experiments had been carried out by radio telescopes to map the red-shift of the 21 cm hydrogen line in the ambient galaxies and to much surprise the extension of (H-I) to a large distance beyond the galactic radii arousing a suspense regarding the excess mass-distribution of the galaxies. Finally the rotational velocity has been observed to peak between (~9 – 12 Kpc) followed by a flattening extending upto $\sim 30\ \mathrm{Kpc}$ suggesting large values of mass ratio to outer parts of the (H-I) disks. The rotational velocity $R(v)_{rot}$ is given by,

$$R(v)_{rot} = \sqrt[2]{\frac{GM}{r}}$$

Where 'G' is the constant of gravity, 'M' is the mass that is enclosed within and 'r' is the radial distance to the galactic disk. Now, the rotational velocity should diminish by $\sqrt[2]{\frac{1}{r}}$ instead it is directly proportional to the "M" as $R(v)_{rot} \propto M$. The DM density distribution is inversely proportional to the square of the radial distance as $\rho(r) \propto \frac{1}{r^2}$. The DM Halo having a mass of $10^{12}\ \mathrm{M}_\odot$ having a radius of $\sim 10^2\ Kpc$ has the average velocity computed by virial theorem as,

$$Halo(v)_{avg} = \sqrt[2]{\frac{GM_{Halo}}{r_{Halo}}} = \sim 200\ Km\ Sec^{-1}$$

The phase-space material in the DM Halo has a certain density governed by the Boltzmann equation,

$$N_{Phase\ Space} = \iiint ._{momenta} \iiint ._{positions}$$

$$f(x^1 x^2 x^3 p_{x^1} p_{x^2} p_{x^3} t) dx^1 dx^2 dx^3 dp_{x^1} dp_{x^2} dp_{x^3}$$

$$x^1 x^2 x^3 \epsilon \mathbb{R}^3.$$

Therefore, for the particle to exist the probability density dictates $\int N_{Phase\ Space} = 1$.

Baryons in the galactic disk (interstellar-medium) can interact among themselves and collide; however, the DM is collisionless and therefore makes a spherically symmetric Halo. This states that the collision operator $\overline{\mho}(f) = 0$ while the equations governing the Liouville operator give the implicit definitions as,

$$\boldsymbol{L}(f) = \dot{\rho} + \sum_{j=1}^{n} \left(\frac{\partial \rho}{\partial q_j} \dot{q}_j + \frac{\partial \rho}{\partial p_j} \dot{p}_j \right) = 0$$

$$\{q_j \rightarrow Canonical\ coordinate, p_j \rightarrow conjugate\ momenta\}$$

No matter what trajectory the DM of the phase space takes $\boldsymbol{L}(f)$ is constant along the path of trajectory implying $\overline{\mho}(f) = \boldsymbol{L}(f)$. As pressure, density, momentum is a function of the gravitational potential ϕ_G the Jeans instability of the enclosed mass $M_{enclosed}$ as a function of the radial distance $'r'$,

$$\frac{\partial p}{\partial r} = -\frac{\phi_G \rho(r) M_{enclosed}(r)}{r^2}$$

Solving the Jeans instability with the gravitational potential and radial dependence, the density distribution becomes,

$$\nabla^2 \phi_G = -4\pi G \rho \rightarrow \rho(r) = \frac{V_{dispersion}}{2\pi G r^2}$$

This satisfies two important relations as,

1. $\rho(r) = \frac{1}{r^2}$
2. $f(v) \propto e^{-v^2/(V_{dispersion})^2}$

This suggests that the DM is capable of gravitational interaction in the spherically symmetric Halo and the density falls as the inverse of the distance squared with the velocity being exponentially falling meaning that the curve is no longer flat.

Some of the direct evidence for the DM-distribution density includes,

- According to the Virial theorem, the kinetic energy of the stars must be binded together by a strong potential force which implies the relation,

$$\langle Time \rangle = -\frac{1}{2} \sum_{i=1}^{N} \langle \boldsymbol{F}_i \cdot \boldsymbol{r}_i \rangle$$

  Where the i^{th} force located at i^{th} positions acting on i^{th} particles over an average time denoted by brackets measured the mass and velocity of the galaxies (either dwarf or not) and globular clusters. However, the dispersion of velocity does not match with the distribution of the masses resulting in a kinetic anomaly. Every galaxy has 'luminous density' and that density decreases as in case of a spiral galaxy, from the galactic center to the arms. In observations, this theory proved fragile, as the luminous masses assumed to be stars with planets orbiting around them, however, the rotational velocity at the arms must be less than that of the centre, but this doesn't happen and this proved some non-luminous matter prevails at the outskirts in the extra-galactic Halos probing firm evidence to DM particles.

- Gravitational lensing paves the way between an observer and a large mass with a source. This result in the distortion of the lights, however, the mass-to-light ratios does not tally the theoretical measurements thereby again proving the existence of DM particles surrounding the massive objects.
- Ordinary matter in the early universe results in ionization potential and they are scattered through Thomson scattering. However, DM does not behave like the ordinary (or baryonic) matters. Therefore in the CMBR, there are remnants of anisotropic peaks which were first detected by COBE satellite in 1992. The power spectrum of these anisotropies can be decomposed into peaks and they provided evidence for DM particles by both MWAP and PLAN satel-

lites. DM does not couple with Electromagnetic particles, therefore it gravitationally interacts with the density and viscosity of the ordinary matter.

- The FLRW metric provides a homogeneous universe where all the structures have been evolved and formed within these 13.8 * 10^9 years. However, those structure formations infer with the logic that, if there is enough gravity only then the formations properly takes place, but the gravity to structure formation ratio is not prominently defined meaning that there exists some missing mass spectrum that needs to be included into account and that recounts for the DM.
- Supernovas (Type Ia) provides a perfect candidate to prove GR, however, the energy-density of the universe $\prod_{Total} \approx 1$ (because the universe is assumed to be flat as $\Omega = 1$) but, the interesting point is $\prod_{Baryons-density} \approx 0.05$ while $\prod_{Dark-energy-density} \approx 0.6$. this leaves the clue that the missing matter $\prod_{DM-density} \approx 0.3$.
- Solan Digital Sky-Survey detected the Baryon-Acoustic-Oscillations of the QGM in the early universe that seemed to provide signatures on CMBR power spectrum, the recombination of the DM and Baryons when occurred, then, the observable effects are weak in the early universe, however, the present day they are clearly noticeable (≈ 1) at galaxies separated by 140 – 148 MPc.

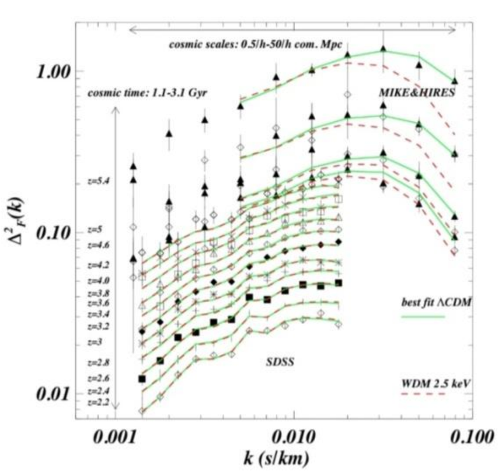

Fig. 3 Power spectrum of Layman-α flux in post Big-Bang era. CDM are shown in green, WDM are shown on red. WDM is exposed to high red-shift [6].

DM falls into 3-categories WDM (warm DM), CDM (Cold DM), HDM (Hot DM)[7] based on their Free-Streaming-Length (FSL). Dwarf Galaxy (D-G) is the main parameter to identify WDM, CDM and HDM. The classification tends 3 scenarios,

1. FSL of (D-G) ≈ WDM
2. FSL of (D-G) ≪ CDM
3. FSL of (D-G) ≫ HDM[8][9]

Furthermore, DM can be classified as $\gamma_{elastic}$ and $\gamma_{in-elastic}$. After the Big Bang, after a considerable amount of time, when the universe is accelerated and cooled it becomes rather difficult for the DM particles to get annihilated with a partner through Axion-Portals or Vector Portals, thereby, the number density of DM N_ρ of $\gamma_{in-elastic}$ 'freeze out' according to the Hubble rate $H = \frac{\dot{a}}{a}$ on the magnitude of,

$$\gamma_{in-elastic} = \langle V_{dispersion} * V \rangle \sim \frac{\dot{a}}{a}$$

The 'Freeze out' temperature of CDM, HDM and WDM are respectively,

- $N_\rho \sim \sqrt[2]{T^3} * \sqrt[T]{\frac{e}{m_x}}$
- $N_\rho \sim T^3$
- $\left(\sqrt[2]{T^3} * \sqrt[T]{\frac{e}{m_x}}\right) \overset{WDM}{\leftrightarrow} T^3$

After the HDM is no longer in equilibrium with the ambient plasma, chemical equilibrium takes place and the thermal state of $\gamma_{in-elastic}$ vanishes, remaining after the decoupling $\gamma_{elastic}$ of the CDM which persists in the present day universe after the thermal equilibrium phase becomes over. Fig. 3 shows the redshift of $z \gtrsim 5$ from 50 different Quasars. The more hotter the DM, the FSL becomes longer and the cut-off rate of kinetic decoupling gets lower. During the early stage the HDM are in random collisions with Photon-bath due to the non-zero average velocity which finally leads to the formation of $\gamma_{elastic}$ CDM.

Jeans theorem and virial theorem applies in our galaxy, providing it exists in a steady state. Our Milky-Way being $\sim 13\ Gly$ old collided with a galaxy in the past about $\sim 10\ Gly$ ago and in the process of merger of the two galaxies (one being dwarf), the core galactic disk perturbs resulting the infilling materials from the collision which ultimately leads to adiabatic contraction where the matter cusps in the galactic disk. However, the density and velocity of the DM distribution remains unchanged in the Phase space according to Boltzmann-Maxwell distributions and the traces left behind by the in-falling stars shows the trail of the DM gases. This includes but not limited to the perturbation of the DM Halos by resultant combining of two galactic mergers where if there exists some supernovas, then this pushed apart the DM gases to the boundary of the Halos resulting a alteration of the distribution of DM gases and particles. 3 successful models can be considered depending on this structure simulations where *N-body* gravitating bodies are taken into account meaning many gravitating systems interact with each other.

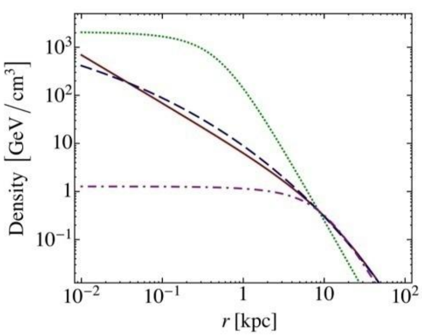

Fig. 4 Simulated comparison of 3 profiles with NFW (red), Einasto (dashed blue), Burkert (green), 10 KPC (dot and dashed purple)[10].

$$\rho_{(r)}^{NFW} = \frac{\rho_0}{(r/r_s(1/(r+r_s)^2)} \text{ [11]}$$

$$\rho_{(r)}^{Einasto} = \rho_0\ exp\left[-\frac{2}{\Gamma}\left(\left(\frac{r}{r_s}\right)^{\Gamma} - 1\right)\right]$$

$$\rho_{(r)}^{Burkert} = \frac{\rho_0}{(1/(r+r_s)(1/((r+r_s)^2)} \text{ [12]}$$

$$r_s \approx 20\ Kpc\ ,\ \Gamma = 0.17 \text{ [13]}$$

These equations (3 of them) give a better understanding of the full hydrodynamic solutions of our Milky-Way galaxy providing the density parameters as a function of radial distance *(r)*, N-body simulations provide a strong evidence for velocity distribution and dispersion where the Halo may get effected by a merger of another Halo or a tidal stream or tail of the remnant matter exists in the outer layer of the disk subject to merger. The DM phase space distribution may have clumps resulting from over density of the dark matter or may have streams of debris detected by the Solan Digital Sky Survey (SDSS). There can be overlapping Halos resulting in the overlapping streams of debris which may accumulated to a DM disk surrounding the Solar Systems accordance with the Phase Space distributions. From Fig. 4 the density of the 3 models, $\rho_{(r)}^{NFW}$, $\rho_{(r)}^{Einasto}$, $\rho_{(r)}^{Burkert}$ falls as $\rho(r) = \frac{1}{r^2}$ at a radial distance of $\gtrsim 10\ Kpc$. The over density accumulation of the dark matter in the 'Solar Disk' is accompanied by an exponential fall of velocity related to $f(v) \propto e^{-v^2/(V_{dispersion})^2}$. SDSS identified 'fields of streams' of DM Particles with some blue shifted nearby and others red shifted across the tails of the debris moving faster outwards.

To search for the astroparticle component of the DM, it is better to know what kind of spin statistics the DMs are following. The DM Halo can be made of a large number of scalar bosons in the $N_{Phase\ Space}$ and therefore, there is no upper bound for the bosons to occupy the DM candidates. They can be well immersed inside the Halo. However, if the DM is a Fermi particle then the Fermi-Dirac statistics makes the existence of DM in the $N_{Phase\ Space}$ quite difficult due to the spin coefficients. The Pauli's exclusion principle dictates that the Fermi-particles can exist in one combination only that is,

$$|\uparrow\rangle\ and\ |\downarrow\rangle$$

However, in this scenario, the cells of the $N_{Phase\ Space}$ must accompany Pauli's principle to accommodate DM particles. As the probability of finding a DM particle as $\int N_{Phase\ Space} = 1$, therefore, the Heisenberg's Uncertainty Principle holds as,

$$\Delta x * \Delta p \geq \frac{\hbar}{2} \backsim 1$$

Where, $\Delta x = 2M_{Halo}$ and $\Delta p = V_{Dispersion}$

The mass limits of the DM particles can be determined as the existing matter particles in the compact Halo as,

$$m_{Bosons} \gtrsim 10^{-21}\ eV$$

$$m_{Fermions} \gtrsim 700\ eV$$

Therefore according to DM candidates, $m_{Fermions} > m_{Bosons}$

Now, considering the particles making up the DM, 3 suitable candidates are as follows,

- Axion is a suitable component of the DM, proposed to solve the Strong-CP Problem of QCD having mass range of $\sim 10^{-4}\ eV$. Axion having the lightest superpartner axino, it can be a direct evidence of the dark matter for the astrophysical signatures detected in the Halo. Axions does not act electromagnetically and the low cross section makes it difficult to interact with the ordinary matter. Axions can be there at the primordial universe at the beginning of the Big Bang and with the ULA or Ultra Light axions, the mass range falls as $\sim 10^{-21}\ eV$ making it a suitable component for Bosonic DM. the high flux of axions from the galactic Halo has been observed resulting a density parameter of $\sim 0.1\ GeV \cdot Cm^{-3}$ indicating that, there must be other DM candidates along-side axions as its density is not sufficient enough to make up the DM Halo.
- FCD or Fuzzy-Cold DM are another hypothetical candidate of DM having a mass range of $10^{-21}\ eV$ or $10^{-22}\ eV$ thereby making a CDM candidate. There always remains a discrepancy between the Inferred DM densities and N-body simulated predictions, therefore, this FCD governed by Poisson-Schrödinger equations can solve the 'Cuspy Probem' of the DM Halos.
- Sterile (or inert) neutrinos having an isospin of $+\frac{1}{2}, -\frac{1}{2}$ interacting only via gravitational forces can be the potential candidate for DMs. They can be labeled as CHL or Charged Heavy Leptons and interacts with the weak processes.

Now, as the Lioville operator is equal to the Collision operator as we see before as,

$$\overline{\mho}(f) = \boldsymbol{C}(f)$$

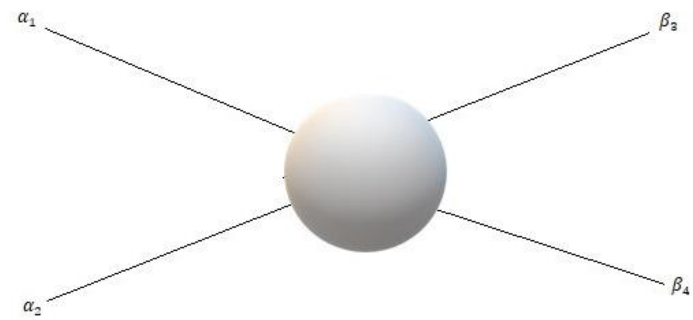

Fig. 5 The $N_{Phase\ Space} \sim 1$, thermal equilibrium and kinetic equilibrium can be achieved when we have 2 incoming dark matter particles $\alpha_1 a_2$ interact with baryonic particles $\beta_1\beta_2$ via vector portal (the grey sphere in the diagram),

The conditions in above diagram is achieved when $\overline{\mho}(f) = \frac{\partial n}{\partial t} + 3Hn$ where *'n'* is the number density over time and *'H'* is the Hubble constant (~ 80) equals to the $\boldsymbol{C}(f) = (\langle V_{Dispersion} * V\rangle n_{\alpha_1} n_{\alpha_2} - \langle V_{Dispersion} * Vn\ \beta 1n\ \beta 2$, where 1,2 are initial DM particles, 3,4 are final Baryonic matter particles, this gives the parameter $\sigma = {number\ density}/{entropy} \approx 10^{-26}\ cm^3 Sec^{-1}$ and according to the PLANK+WMAP data, the coupling parameter is ~ 0.1 then the $m_{DM} \sim 100\ GeV$.

DM are abundant in the extra-galactic regions, the centre of the galaxies (the Halo around the galactic disc), and the Dwarf-Galaxies. All these measurements are indirect measurements and comes from satellites or orbiting spacecrafts, which detects the DM annihilations as,

$$\beta_1 + \beta_2 \to Z^0, W^+W^-, \overbrace{q\bar{q}q\bar{q}}^{hadronisation} \to \gamma\gamma$$

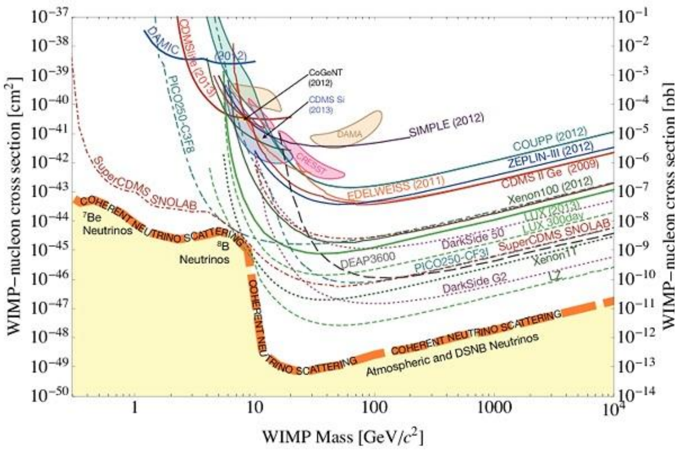

Fig. 6 Deferent source for DM scattering with the yellow region depicts the neutrino scattering as Sterile (or inert) neutrinos also fall in the CDM regime and can't be separated from the signal[14], 10 to 90 GeV is the regime where the nucleus can't giggle anymore their recoil energy being $\sim 10\, GeV$ while after 100 GeV, the number density increases as mass decreases.(for the XENON atoms)[15].

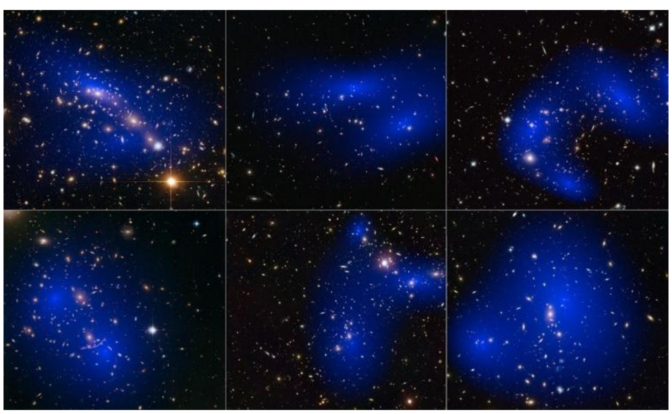

Fig. 7 The six cluster collisions of the DM mapping the galactic distances (CC BY 4.0 Wikipedia) probing indirect detection of the DM in cluster galaxies and the merger of the galactic Halos when they collides with each other[16].

However, in the ground based detections, the XENON (in XENON100 experiments)[17] is placed to some underground mines or facilities for protecting against radiations and high energy cosmic rays, where if the DM candidates of mass m_0^{DM} hits a nuclei and scatters them then the resulting mass of the DM after scattering becomes m_1^{DM} such that $m_1^{DM} - m_0^{DM} \sim \delta$. The XENON nuclear mass is around $\sim 120\, GeV$ with the recoil energy $\sim 50\, GeV$ having the threshold energy limit of around $\sim 10\, KeV$. The underground detectors have been developing around the world for DM detection.

Collider experiments are another essential source for detecting DM particles. DM particles are hypnotized to be lighter than other standard model particles although they can give hints of the unknown supersymmetric particles. There may lies an entire landscape of this DM particles beyond our sight of view. Those particles as doesn't interact with lights or other electromagnetic radiations, they are difficult to detect from the tracks left in Proton-Proton collisions of LHC or Proton-Electron Collisions in LEP. However, when the atom bombardment takes place in the collider, those DM particles dissipate very quickly in space and hence remain undetected. Those are observed from the momentum and energy (missing) from the total momentum of the collisions. This can also be possible that DM escapes to the other dimensions. In this case DM must have to be a BOSON obeying BOSE-EINSTEIN statistics and they are not bounded by Dirichlet-boundary conditions. So, two things can be concluded,

- Either they dissipate quickly in space before getting detected and hence left undetected.
- Or, they are closed strings without any boundary conditions or attachment and thereby escape to higher dimensions of space-time.

The proportion of DM to ordinary matter is 5:1. Hence DM is abundant in the universe (or observable universe)

The critical energy density of the matter curve is given by,

$$\rho_0 = \frac{\rho_{total}}{\rho_{critical}} = \sum \rho_i$$

Here $\rho_{critical} = 1.88h^2 \times 10^{-29} gm\, cm^{-3}$ and ρ_i is the stars, photons and other matters in the observable universe. CMBR gives us a picture of the universe at around $\sim 3{,}00{,}000$ Yrs after Big Bang. The anisotropy of the CMBR is the last scattering that helps us to determine the matter distributions or the acoustic oscillations that resulted when DM annihilates to photons which shows us a sudden spikes in the curve of radiation distribution. The CMBR anisotropy is the best means to determine the ρ_i of the universe[18,19].

$$\rho_i = \rho_{Baryons} + \rho_{DM}$$

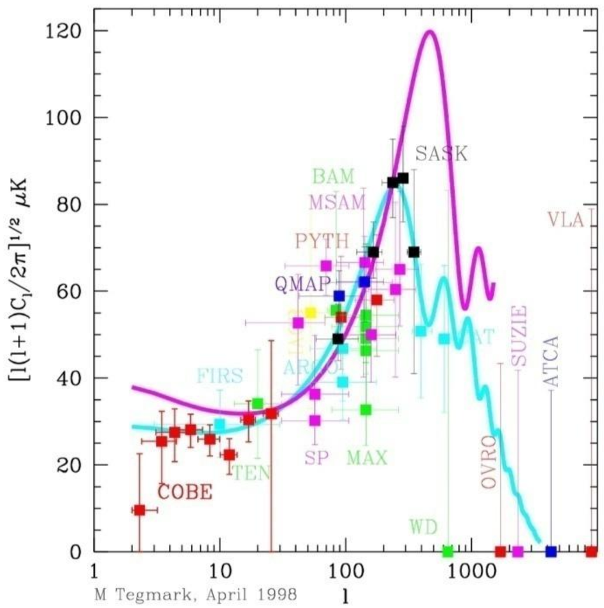

Fig. 8 The summary of the anisotropy measurements of the CMBR at $l = 200$ at $\theta = 1$ with the spike being shown as the photon spikes distributions in the universe. (Figure courtesy: M. Tegmark)

MACHOS can be a dominant factor of DM contribution in the galactic Halos, however, its difficult to detect because they generally consists of black holes, black dwarfs which doesn't have any luminosity to get detected. However, if a consecutive portion of DM are in Halos by means of MACHOs then they can range from masses $\gtrsim 10^{-8}M_{\odot}$ and gravitational microlensing is the only method to detect them by observing a star passing by the line of sight which temporarily brightens when they encounter MACHOS. The EROS and MACHO collaboration spends several years for this microlensing effects and candidate events have been detected of masses around $\sim 0.1M_{\odot}$, however for small dark objects they can be as less as $\lesssim 10^{-3}M_{\odot}$.

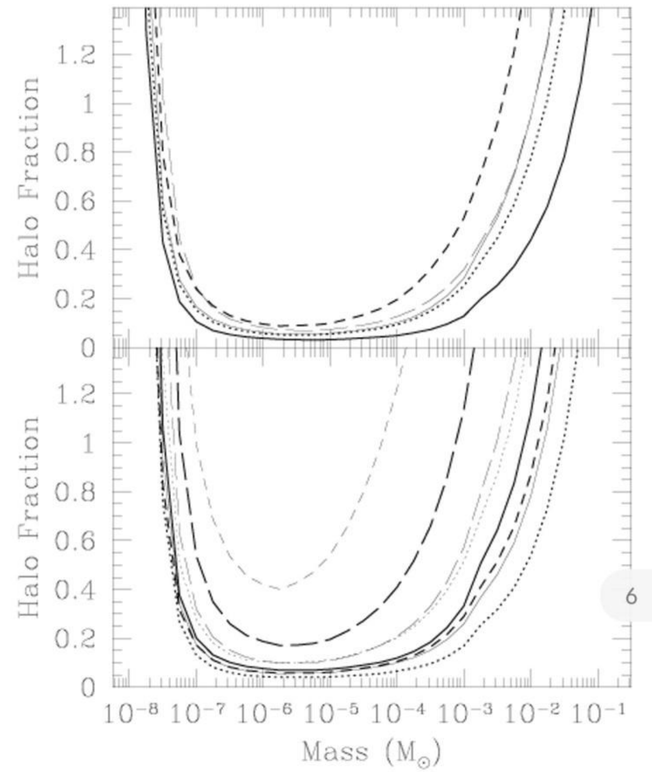

Fig. 9 The HALO-Fraction of the Milky Way attributed to machos as a function of their mass as attributed to EROS collaboration (upper) and MACHO collaboration (lower) with each curve representing a 'standard Halo[20].

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