3. Dark Matter (Evolution History of the Universe)

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1 Introduction

With the creation of the first star, the formation of large-scale structures began and ultimately evolved into the present universe. Regarding the structure formation, two scenarios have been proposed: *top-down* and *bottom-up*. In top-down scenario, clusters form first and fragmented into galaxies. However, this scenario is not much appreciated and theoretical and observational indications rule this out. In bottom-up scenario, primordial seeds of the universe formed protogalaxies which formed galaxies and then merged into cluster and then superclusters. This formation is favored by observations. This structure formation is spanned over the course of billions of years and is still continued today. New stars are being born and old stars are dying.

In all this situation, one thinks if universe is composed of all the mighty cosmological objects then how much all this stuff weighs? How much universe weighs? Before weighing universe, we must know where all the matter of universe is located. This matter is divided into two categories, one which is known to us and emits light and second is little bit mysterious, somehow unknown to us, neither emits nor absorbs light of any wavelength.

The most prominent and largest sources of visible matter are the stars and the most easy and well-known way to look at stars in larger regions. These mighty stellar objects emit photons of different wavelengths such as visible, infrared, ultraviolet, in all directions. But they only contribute to 0.3% of the total energy density of the universe. Even if we consider other stellar and sub-stellar objects such as neutron stars, black holes, black and brown dwarfs, this density parameter will still be much less than the observed one [1].

Despite of the fact that it is not an easy and handy task to detect all of the baryonic constituent of universe, it is still interesting that nearly 85% of the baryonic matter of the universe is in the form of interstellar medium (ISM)[1] and a slender gas in intergalactic space[2]. Howbeit, big bang nucleosynthesis constrains that critical density of the universe cannot be comprised of normal material only otherwise the present abundances of light elements will not agree to the observations. Even if

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[1]Interstellar medium is the matter and radiation that exists in the space between the star systems in a galaxy. This matter includes gas in ionic, atomic, and molecular form, as well as dust and cosmic rays. (Source: Wikipedia)

[2]Intergalactic space is the physical space between galaxies. It's almost empty, but not quite, as there are gas particles and so on floating around.

we consider CMB radiations along with BBN, this baryonic matter density parameter will still be less than the total energy density of the universe [1].

Situation becomes more worse, when it is known to us that not only we are unable to detect a large percentage of baryonic matter, but the major constituent of critical density of the universe is not even baryonic. In 1932, Jan Oort was observing sun and other stars in Milky Way when he postulated the existence of this hidden constituent of universe, local dark matter [2]. A strong evidence for Oort's observations was put forward by Fritz Zwicky in 1933 during the study of red shifts of galaxies in Coma cluster (Abell 1656) [3]. He found that individual velocities of galaxies is much greater than the mean velocity of the cluster. In this scenario, cluster cannot be hold in the form it is, because of strong gravitational pull. The only way to shield from expansion is the assumption of some invisible matter which can provide enough gravitational force. Zwicky called this invisible matter *dunkle Materie* i.e. dark matter.

Since, dark matter does not emit, absorb and scatter light, so it makes it quite difficult to detect. It is theorized, it can interact only with conventional matter via gravitational force. Direct interaction is near to impossible to detect with modern day technologies. However, its gravitational influence on visible matter can be studied by inspecting orbital speeds of stars in spiral galaxies[3] for example, Milky Way and Andromeda (M31). At a length scale of few kiloparsec, the mass of star inside that radius becomes essentially constant and if stars contribute all (or most of the) mass of the galaxy and orbital velocity will be proportional to the inverse square root of the radius. This is called Keplerian rotation. Using this, Kepler found that 99.8 percent mass of the solar system is contained within the sun. In 1970, when Rubin and Ford calculated the orbital velocity of Andromeda at different radii, using the Keplerian relation, they didn't find any decrease in the Keplerian velocity and found it to be nearly constant. This cannot be possible unless stars contributes to most or all of the galaxy mass [1]. It provided a strong evidence for the presence of 'dark halo' (dark matter).

1.1 Classification of Dark Matter

Usually dark matter is classified in three categories: *hot, cold* and *warm*. Although, these terminologies have nothing to do with the degree of temperature. This classification is based on the distances travelled by the particles before they scatter, that is, free-streaming length (FSL). This classification of dark matter also guides us about the structure formation of dark matter that either it follows bottom–up formation or top–down structure.

Hot dark matter (HDM) is constituted of particles having ultrarelativistic speeds and their free–streaming length is larger than a protogalaxy[4]. HDM favors the top–down formation of the universe, that is, early universe first formed into larger groups of clusters and superclusters and then with the passage of time, it is started fragmented into smaller galaxies and other cosmological objects. But the data of CMBR acquired by COBE[5] discards the top–down formation and verifies the uniform and smooth formation of the universe. This formation is also unfavored by the observation of high redshift of the galaxies. Moreover the ultrarelativistic speeds of particles cannot allow these particles to clump together to form larger cosmological structures. Active neutrinos are thought to be one of its main candidate.

[3] In a spiral galaxy, the stars, gas and dust are gathered in spiral arms that spread outward from the galaxy's center. (Source: https://coolcosmos.ipac.caltech.edu/ask/217-What-is-a-spiral-galaxy-)

[4] It is the large concentration of gas and dust from which a galaxy is formed. It is also called as "primeval galaxy".

[5] Cosmic Background Explorer or Explorer 66

Cold dark matter (CDM) is composed of particles having smaller speeds than the speed of light and their free–streaming length is much smaller than a protogalaxy. It favors the bottom–up formation in the universe, which makes it capable to explain the formation of galaxies and cluster of galaxies. This is responsible for the genesis of large–scale structures in the universe. CDM is thought to be the most perfect and successful interpretation of dark matter and structure formation of the universe. CDM also gives us an inkling of the presence of non–baryonic dark matter along with baryonic dark matter. There are a number of proposed candidates for CDM which spans from sub–atomic particles to intergalactic objects. Its proposed candidates are axions, MACHOs, thermal WIMPs and supersymmetric particles. Having well–established theoretical framework, there are some proposed properties of CDM candidates.

Mass CDM candidates should be massive (greater than 1 keV) along with a longer–life.

Collisionless CDM particles should be collisionless, that is, they should only interact via gravity, even significant self–interactions are also interdicted.

Dissipationless They should not be cooled by radiating photons as ordinary baryonic matter does (and did) to form galaxies. With collisionless and dissipationless nature, they can form halos in spite of galactic structures [4]. But it is ticklish somehow because a massive particle, with no electric charge, will be mediating through long–range and surely will have a some kind of dissipation [5].

Lifetime Life–time of these particles must be comparable to or larger than the age of the present day universe.

Warm dark matter (WDM) lies in between hot and cold dark matter. Particles which constitute WDM have comparable free–streaming length to a protogalaxy. Its predictions are quite similar to cold dark matter but with a clear difference of small–scale density perturbations, that is, it predicts less abundance of dwarf galaxies which is a consequence of low density of dark matter in the central bulge (part) of larger galaxies. Its proposed candidates are sterile neutrinos, gravitinos and non–thermal WIMPs.

1.2 Candidates of Dark Matter

In cosmology and particle physics, there is no shortage of proposed candidates for dark matter. Holy moly, they are as smaller and lighter as neutrinos and on the other hand, as massive and bigger as black holes. It shows the variety of proposed models and also the lack of our understanding about dark matter.

Usually, dark matter is classified into two categories, based on the nature of candidate, either baryonic or non–baryonic. Since, we are interested in categorizing dark matter candidates on the basis of classification of dark matter, so it is better to get an overview of baryonic and non–baryonic dark matter first.

Baryonic Dark Matter Big bang nucleosynthesis put a constrain that dark matter cannot be baryonic otherwise the present density of light elements would be different [6]. But it is also thought, a smaller part of dark matter can be baryonic. Unlike other baryonic material, it is surely be non-luminous and cannot be observed directly. However, its presence can be observed indirectly via its gravitational effects on visible matter. Several candidates were proposed for baryonic dark matter which include dust, clouds[6] of hot and cold gas, snowballs of frozen hydrogenic matter such as comets and collapsed stars, brown dwarfs etc. Dust and clouds of gas were rejected while the others were added into MACHOs along with some other proposed candidates.

Non–Baryonic Dark Matter Since a large part of dark matter consists of non-baryonic particles which do not radiate, absorb or scatter light, so there are dozens of different proposed non–baryonic candidates. But the most popular three candidates are neutrinos, axions and weakly interacting massive particles (WIMPs).

1.2.1 Candidates of hot dark matter

Active neutrinos

Standard Model neutrinos or active neutrinos are the lightest known fermions. They are electrically neutral and interact only via gravity and weak nuclear force. Being relativistic and collisionless particles, they favor top–down formation of the universe. But their relic mass density indicates that there are no ample active neutrinos in the universe to be the dominant dark matter. Moreover, their upper mass limit is much greater than the theoretically predicted mass limit of neutrinos which can make dark matter. However, it is still thought that may be sterile neutrinos are a constituent of dark matter.

1.2.2 Candidates of warm dark matter

Sterile neutrinos

Sterile neutrinos, proposed in 1993 by Scott Dodelson and Lawrence M. Widrow [8], are heavier than active neutrinos. They have slower speeds, do not take part in neutrino oscillations and interact only via gravity. Their mass can be from less than 1 eV to 10^{15} GeV. They were also proposed to be the candidate of CDM, by Xiangdong Shi and George M. Fuller [9], if they are produced non–thermally with a very small lepton asymmetry under the mass limit from 100 eV to 10 keV.

1.2.3 Candidates of cold dark matter

MACHOs

MACHO is an acronym for **M**assive **A**strophysical **C**ompact **H**alo **O**bject. They include white dwarfs, neutron stars, brown dwarfs and even black holes. But they are not accounted for all dark matter, present in the universe. They are composed of non-luminous and non-radiating baryonic matter. MACHOs were detected in 1993 by gravitational microlensing. In gravitational microlensing, MACHOs are detected when they are in front of or too close of a star such that their gravity bends the starlight and as a result, star appears brighter. But this is one of the most rarely happened phenomenon in the universe. Usually, millions of stars are observed to detect gravitational microlensing. Soon after their discovery, scientists started thinking that the problem of dark matter

[6] To cosmologists, dust means any form of matter which does not exert a pressure which is comparable to its energy density, or in other words any form of matter which is cool enough that its particles are not moving at relativistic speeds. Most cosmologists think of entire galaxies as constituting the grains of this dust! [7]

has been solved but it's a hard nut to crack.

Primordial black holes

Primordial black holes are also one of the proposed candidates for dark matter. They formed before the big bang nucleosynthesis, in the early universe. They are non-radiating and non-luminous. They have a longer lifetime than other proposed candidates. They are the most massive in the list of proposed candidates for dark matter. Their mass is in the range of 0.3 to 30 solar mass[7] but according to some theoretical predictions, it can exceed to 100 solar mass. Some astrophysical observations also restrict their mass limit to 10^4 to 10^5 solar mass [6]. It is also theorized that they can only be formed in the center of a galaxy. Howbeit, they are not observed yet.

Thermal WIMPs

WIMP is an acronym for **W**eakly **I**nteracting **M**assive **P**article. As the name suggests, WIMPs are massive, non–relativistic, electrically neutral, weakly interacting and non–baryonic constituent of dark matter. It is theorized that they interact with ordinary matter via gravity only although some scientists are also of the view that WIMPs interact via some hidden force too. WIMPs are available in two classes, based on their production: thermal and non–thermal. Being a strong candidate of CDM, scientists are interested only in the thermal production of WIMPs. In the early universe, when the temperature was too high and the universe was in thermal equilibrium, the number densities of photons and WIMPs were nearly equal. But as the temperature started falling and the universe cooled down, number densities of both species started decreasing. There was an exponential decay for WIMPs while the creation of new WIMPs became rare. If this equilibrium lasts forever or till today, then we're left with very few WIMPs. But it is not so and we assume that at some point number density of WIMPs was so low that probability of annihilation became minuscule and inconsequential. It results in stable WIMPs and those WIMPs are thought to be the major constituent of dark matter today. Precise nature of WIMPs is still unascertained because of undiscovered particle but SUSY predicts many undetected WIMPs. Its proposed particles include neutralinos, photinos, gluinos, sneutrinos, axinos, gravitinos, Q-balls and the list still goes now. However, all of these particles are hypothetical yet [10].

Axions

Axions are non–relativistic collisionless hypothetical particles, proposed in 1977 by Peccei–Quinn theory to resolve the strong CP problem in quantum chromodynamics, but they are not detected yet. Being electrically neutral, if they exist, there mass range will be from μeV to meV [11]. They produced non–thermally and interact only via gravity and electromagnetic force with ordinary matter which suggests that they were never in thermal equilibrium with known matter. It makes them one of the strongest non–baryonic candidates of dark matter. Since they have a very small velocity dispersion, so they also qualify to explain the large–scale structure of the universe.

Supersymmetric candidates

Supersymmetry (SUSY) is a theory which defines a relation between two fundamental classes of particles, bosons and fermions. According to SUSY, each bosonic and fermionic normal parti-

[7]The solar mass is a standard unit of mass in astronomy, equal to approximately 2×10^{30} kilogram. (Source: Wikipedia)

cle has fermionic and bosonic superpartner respectively. Bosons have fermionic superpartner for example gravitino, higgsino, wino, zino, chargino, photino, gluino, axino etc. and fermions have bosonic superpartner such as squark, selectron, smuon, sneutrino etc. Although, there are certain supersymmetric particles with same set of quantum numbers, so they can be superimposed to make an arbitrary particle which is not superpartner to any other particle for example neutralino. Mass scale for supersymmetric particles is around 10^{16} GeV [10]. Since supersymmetric particles cannot decay into normal particles of the Standard Model, so the lightest supersymmetric particle (LSP) will be stable.

Neutralinos

Neutralino is the superimposition of photino, higgsino and zino. Neutralino is thought to be LSP and it makes it one of the most important supersymmetric candidates for dark matter.

Gravitinos

Gravitino is of different nature than other supersymmetric particles. It is often called super–WIMP because of much weaker interaction strength than other particles, with a mass scale around 10^2 TeV which makes it suitable for CDM. It depicts only gravitational interaction. In some SUSY models, its mass scale is around keV. These models predict it to be LSP and a candidate of WDM.

Sneutrinos

Sneutrinos are the superpartners of active neutrinos and they were thought to be the constituent of dark matter but they were discarded because they annihilate quickly and to be consistent with DM, their masses must be greater than 500 GeV. Moreover, their elastic scattering cross–section with nuclei is much larger than the scattering cross–section limits of dark matter, typically it is in the order of femtobarns (fb) [12].

Axinos

Axinos are somewhat similar to gravitinos. They also belong to the category of super–WIMPs or exceedingly weakly–interacting mediating particles (EWIMPs). Their mass can be from eV to GeV and can be produced both thermally and non–thermally [13].

With this, we have completed our discussion on dark matter and in the next post, we will try to review dark energy. Links to previous blog posts of this series are:

1. Evolution History of Universe (A Story from Zero to Ten Seconds)
2. Evolution History of Universe (From 10 Seconds to 10 Billion Years)

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