Dark Matter

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Abstract: In this paper, we introduce the astrophysical problem of dark matter (DM) mainly focusing on the observational/experimental point of view. Even though DM cannot be observed directly, there are plenty of indirect observations supporting that there is more mass than we can see. This is the case for the observed properties of galaxies, galaxy clusters and the large-scale structure of the universe. We mention the implications of DM in astrophysics and high-energy physics. We then describe the DM candidates. The first group is the ordinary DM, also known as baryonic DM, in the form of astrophysical objects. The second group is non-ordinary DM or non-baryonic DM. This group encompasses all the solutions for the problem that are not in the Standard Model (SM) of particle physics. We end up by reviewing some current experiments that could allow us to discover what kind of DM we are facing.

I. INTRODUCTION

Dark Matter (DM) is currently the problem of greatest importance for cosmology together with dark energy. We know that DM is composed by particles that do not emit, absorb nor reflect light, which implies that it cannot be detected through electromagnetic radiation observations. We know that DM exists because of its gravitational effects on ordinary objects that we see. Since the discovery of DM physicists have produced many theories about what it may be formed of or if it even exists. Many of these theories have been discarded over the years because new evidences were found, but still we have no definitive theory. The importance of understanding DM is it has notable implications on our universe and its astrophysical or elementary constituents.

II. OBSERVATIONAL EVIDENCES

A. Origins of the problem

The first person to ever introduce the concept of DM, and the one who gave it this name, was Fritz Zwicky in his paper of 1937 where he analyzed the dynamics of galaxies. In this paper he measured the velocities of a giant cluster of galaxies. He observed that though they had speeds of 1.000 km/s these galaxies did not split apart so it needed to be some sort of force that tied the cluster all together. He supposed that the force had to be the gravity but that only raised more questions since the mass needed for such deed had to be 100 times the apparent mass of the galaxies in the cluster, and so he proposed DM as the answer to his problem. Even though Fritz Zwicky was the pioneer that introduced the concept, the missing mass problem was originated in the same year by Horace Babcock. In his paper he obtained the rotation curve of galaxy Andromeda allowing him to find a mass-to-light ratio of 6:1, he was surprised by this value since it was 2 and a half times bigger than the ratio that he obtained by measuring our surroundings. This ratio was later recalculated in Zwicky's paper where he estimated the ratio in 500:1. We now know that it is approximately 300:1. This result seemed to Zwicky so large, with respect of the expected value, that he proposed other methods to find the ratio in an empty effort to correct his value [1].

For the next 40 years, the missing mass problem was left aside, that is because the knowledge of the early universe was very scarce, before accepting DM as a solution of the missing mass problem, scientists needed an early nucleosynthesis model. That was a problem since in the 1940's there was no established model for the Big Bang and the nucleosynthesis so the concept of DM was just an assumption until the early 1970's with Vera Rubin's work.

Rubin studied the rotation curve of galaxies, continuing the work left by Babcock and Oort among others, finding a discrepancy between angular motion in galaxies based on visible light and the observed motion. In her work Rubin calculates the mass needed to explain the galaxy rotation problem, the premise of this problem was that the rotation of the galaxies should threw the stars flying apart if the only mass pulling them together was the visible one. The results of such calculations were that it needed to be 6 times more mass than observed. Over the next decades Rubin's results were confirmed.

B. Current evidences

Nowadays we have more evidences pointing to DM as the solution of the missing mass problem. These evidences are crucial since they give physicists some leverage to work with, and we can split them in 3 groups: the observational evidences of galaxy clusters, the observational evidences of elliptical galaxies and the cosmological evidences of the universe at a larger scale.

When we observe a galaxy cluster we can see a powerful source of X-ray radiation coming from the hot gas in the center of the cluster. We start the process assuming that the X-ray emission follows a thermal distribution and also assuming both hydrostatic equilibrium and spherical symmetry. By doing so we can find a relation between the observed temperature of the gas with the mass of the cluster. With an observed temperature of 10 keV this relation leads us to a substantial amount of DM in the cluster, in fact the observations suggest that 80% of the core mass of any galaxy cluster is made of DM.

Another evidence of the existence of DM when observing a galaxy cluster is the gravitational lensing effect, which distorts the image we receive of the cluster making us observe multiple images of the same object or magnifies the image the object. This is because, as general relativity dictates, a massive object affects the trajectory of light. In clusters the lens is strong enough to produce strong gravitational lensing that can produce multiple images, arcs and even Einstein rings.

We can also obtain useful data when analyzing the halos of elliptical galaxies, these halos have such high temperatures that they emit X-rays when cooling through Bremsstrahlung. One again we make the assumption of hydrostatic equilibrium obtaining a relation between the mass of the galaxy and its temperature. But measuring the temperature has proven to be rather difficult and only in galaxies that lie at the center of a rich cluster we have been able to obtain it, but in this cases we have obtained a mass ratio that implies that around a 95% of the mass is DM[2].

Until now we have been talking about purely observational evidence but there is also a more theoretical way to justify the need for DM in our model of the universe and that lies in Einstein's general relativity theory. If we assume an isotropic and homogeneous universe in expansion we can find the Friedmann-Robertson-Walker metric that when applied yields the Friedmann equations, which relates the value of the Hubble constant with the mass and energy density, i.e. the density parameter Ω, which is the sum of ordinary matter, DM and dark energy, and depending of its value we have different geometries for the universe. With the Hubble constant and the observations, we predict a flat universe which implies a $\Omega = 1$. With the WMAP (Wilkinson Microwave Anisotropy Probe) data of the CMB (Cosmic Microwave Background) we can find the value for DM $\Omega_{\mathrm{DM}} = 0.3$ that implies that almost 25% of the universe mass is DM. Using precise information of the density of ordinary matter that the Big Bang nucleosynthesis gives us we find $\Omega_b \approx 0.04$, implying that there is not enough matter to reach the expected value.

III. IMPLICATIONS

A. For astrophysics/cosmology

1. *For galaxy formation*

In the early universe there was the phenomenon of cosmic inflation, that means an exponential expansion of the space. This cosmic inflation produced what we call primordial fluctuations in cosmological density, entailing density variations in the early universe which are considered the seeds of all structure in the universe[3]. At decoupling of radiation and baryons, DM was already decoupled and in doing so it gave rise to fluctuations of density on galaxy scales, which we call DM halos. Since DM interacts with ordinary matter through the gravitational force and in this early universe ordinary matter was in form of baryonic clouds, these halos provided most of the gravitation which contracted the protogalactic clouds and formed the first stable structures in the universe. Instead, the theories that faced this problem using purely baryonic models found an inconsistency since there is not enough time between the recombination epoch and the present for the structures we see in the early universe to grow.

2. *For primordial nucleosynthesis*

All baryonic matter in the universe partook of the Big Bang nucleosynthesis. If DM were baryonic it would give rise to a higher abundance of light elements. If we observe the primordial density of the ordinary elements that were present in the early universe we obtain what we call the SBBN (Standard Big Bang Nucleosynthesis) theory. This theory predicts a ratio of baryons to photons that allows us to calculate the mean cosmic baryon density. The value of this mean density implies that most baryons in the universe are visible and not dark. Also, we can use this value to calculate the baryonic density parameter $\Omega_b \approx 0.05$ implying that almost 85% of matter exists in form of non-baryonic DM [4].

There was another model for the early nucleosynthesis called the inhomogeneous model since it allowed the possibility of cosmic baryon number fluctuations on small scales in the early universe. These fluctuations would have changed the production of light elements during the BBN giving a higher production of baryons. It was hoped that this model could give a baryonic density of 1 discarding the existence of non-baryonic particles in the universe. Later calculations proved this IBBN model incorrect since it was not consistent with the observed universe, for instance a considerable overproduction of light elements such as lithium or helium[5].

B. For particle physics and high-energy physics

1. *Beyond the SM*

As we have seen in the last section DM should be found in form of non-baryonic matter that the SM does not predict. This discrepancy leads to the conclusion that our current model has some flaws. Such are the problems of the SM that new theoretical developments called physics beyond the Standard Model (BSM) were conceived.

One of the problems of the SM is that it does not explain the phenomena of the neutrino masses, since in the SM neutrinos are thought to be massless. However, neutrino oscillation experiments have shown otherwise. It has been tried to add in the model the mass terms of the neutrinos but that leads to more complications. Apart from this dilemma we have the dark matter and dark energy issue that we have started with. We know as it has been shown in the last section that current cosmological observations predict that only 5% of the universe is explained by the SM. For the rest an approximately 26% would be dark matter which the SM has no viable candidate to explain, and the rest would be dark energy.

2. *New gravitational theories*

There is also the possibility that the problem is not related to the content of the energy-momentum-tensor, but to the gravitational theory itself. Such is the theory known as MOND (MOdified Newtonian Dynamics) that proposes a modification of Newtons laws to account for the properties observed in the galaxies, such as the speed of the stars in the galaxies. This theory was created in 1983 by Mordehai Milgrom. In 2004 Jacob Bekenstein formulated the relativistic version of the MOND with his Tensor-Vector-Scalar gravity (TeVeS) theory, but this theory also fails in front of the evidences of the Bullet Cluster. Both theories had a problem. It still needed some unseen matter in galaxy clusters, but the biggest challenge for this theory came in 2006 with the observation of the "Bullet Cluster". MOND theories predict the missing mass to be centered on the visible mass, opposed to be on the halo, but in the observation of this cluster it was clearly seen an offset of DM from the visible mass.

The other alternative theories are the modifications of general relativity. We know that the Einstein field equation in general relativity is a relation between the Einstein tensor and the energy-momentum tensor. Dark matter and dark energy come from corrections in the energy-momentum tensor to adjust the equation to the observations, but it could also be that the part of the equation that needs to change is the Einstein tensor. In this group, we find the f(R) gravity theories, in these theories instead of the Hilbert-Einstein action written supposing it to be lineal with the Ricci-scalar (R) it is supposed that the action depends on a function of the Ricci-scalar, which have a relation with the curvature of the tensor. This way different dependences of the Ricci-scalar produce different f(R) theories. The other group of theories are the f(T) gravity theories these ones suppose that the Lagrangian is an analytic function of the torsion scalar T. Here the torsion plays the role of the curvature in the f(R) theories, but they are not equivalent. The main problem with these theories is that none of the predictions have been yet confirmed [6].

IV. DM CANDIDATES

A. Baryonic dark matter

As we have seen from the galaxy and nucleosynthesis this type of DM is most likely to be found in the galaxy, particularly in the halo, in the form of astrophysical components.
The first candidate we are going to see in this part is diffuse matter composed by dust and gas. Dust though is not a viable solution since it would imply too much light extinction, so we are left with only the gas but it also has a problem because with the mass density required this gas would have such high temperature that it would emit soft X-rays. Having said that we could have cold molecular H_2 clouds in the galaxy contributing to the halo DM density.
Now we will introduce the galactic compact objects, that we will split into small solid objects ($M \ll M_\odot$), planet-like objects and brown dwarfs ($M < M_\odot$) and lastly very heavy galactic objects ($M > M_\odot$)[7].
In the small solid objects, we find the snowballs, that are condensations of hydrogen with a predicted mass of 1g to avoid being disrupted by collisions. There are some arguments against this type of DM for example Hegyi & Olvier argued that these snowballs would have been evaporated by the microwave background. Also, since we only expect hydrogen to condensate that would imply a high abundance of helium. This suggest the fraction would be no more than 30%, which is not compatible with primordial nucleosynthesis.
For the planet -like DM we have the small balls of hydrogen that are Jupiter mass balls with a very high M/L ratio. The nearest of these objects would be placed at approximately 0.4 pc away, that means near the Oort cloud. This objects due to the low temperature would emit in the 2 to 10 micron wavelength, so it would be observable from the earth if it is no further than 1 pc. In the same category, we can find the brown dwarfs that consist in star-like objects with mass lower than 0.08 $M_\odot$ so unlike the stars on the main sequence this dwarf stars are unable to sustain nuclear fusion, this fact makes this objects a probable candidate for DM. Since 1995 we have confirmed the existence of this dwarfs in the galaxy.

Lastly we have the heavy objects in the form of star remnants. Starting with the white dwarfs these are the natural end-state of a main sequence star between 0.8 - 8 $M_\odot$ and, because of their natural cooling, they could fade below the detectability point if they had been created early enough. The fraction of the original star that is left in the white dwarf remnant is low but one could still produce a lot of DM if there were many generations of stars (Larson, R. 1986). The only problem is that in the process of formation for these white dwarfs a lot of helium is ejected which we do not detect in the halo. The same occurs with the neutron stars that even though they might be a viable candidate their creation would imply high quantity of heavy elements in the halo that are not observed, making these two candidates unlikely. So, we are only left with black holes but only those above the critical mass where the star remnant undergoes a complete collapse without ejecting anything (200 $M_\odot$), but they also have an upper limit ($10^4 M_\odot$)since very massive remnants would disrupt the halo globular cluster and nearby dwarf galaxies[8].

B. Non-baryonic dark matter

In this section, we are going to see the possible solutions and candidates to the DM problem that are outside the SM predictions. We will divide this section in three parts, starting with the DM particles that in the past interacted with ordinary matter but now-a-days only interact weakly. Then we will introduce the axions and finally the DM particles that have never interacted otherwise than gravitationally except maybe whit itself.

In the first type of non-baryonic DM we find three main models the CDM (Cold DM), the HDM (Hot DM) and the WDM (Warm DM). CDM is a hypothetical DM whose particles move slowly compared with the speed of light. No known matter meets the required properties to be a CDM candidate but we have some hypothetical ones that could, like the WIMPs (Weakly Interacting Massive Particles). WIMPs would be new elementary particles that only essentially interact via gravitational force. Also, these particles must have been produced thermally in the early Universe, similarly to the particles of the SM as foretold by the Big Bang cosmology. In this group we can find the particles generated because of supersymmetry (SUSY), which stipulates that every boson has to have a fermion superpartner and vice versa. These particles are very massive ($\sim$ 1 GeV) and the best candidate is the neutralino. Another example would be the superheavy DM, generically called Wimpzillas, these candidates are thought to have been not in thermal-equilibrium during the freeze-out, around 1 second after the Big Bang. Next up we have the HDM here we have particles that travels with relativistic velocities. This model is unable to explain how individual galaxies were formed after the Big Bang, therefore is no longer viable as a sole explanation for DM. The subset of particles considered to be HDM are the only ones known to exist, the neutrinos. Lastly in this part we have the WDM, this hypothetic DM is a inbetweener of the CDM and the HDM. The most common particles for this model are the sterile neutrinos. These are particles that are like normal neutrinos saving for the fact that they are much more massive (10 keV) and do not interact with the weak force. We also have the gravitino as a viable WDM candidate, this is a theoretical particle born form the supergravity theory but we have yet to find evidence of their existence. One last candidate for this model would be the non-thermalized WIMPs [9].

The next solution we are going to talk about is the axion, a hypothetical elementary particle postulated by Peccei-Quinn theory to solve the strong CP violation problem, and if they have a mass in a specific range they could be a possible CDM candidate. If axions have a low enough mass, so they do not have any decay modes, then they would form Bose-Einstein condensates that filled the universe giving an explanation on the DM problem.

In this last point, we introduce the possibility that DM while only interacting gravitationally with the ordinary matter can interact in other ways with itself, trough the so called dark electromagnetism [10]. This was the theory of Sean Carroll, proposing that as regular matter interacts with the electromagnetic force through photons, DM would do the same with their analogous dark photons. Since these dark photons would not interact with the ordinary matter we will not be able to see their light, thus explaining why we cannot observe DM. Recently in experiments of Berillium-8 disintegrations it has been found a discrepancy that they have associated to a bosonic interaction between a pair electron-positron and a new boson, called the x-boson, that could explain also DM interactions.

V. EXPERIMENTS TO DETECT DM

A. Baryonic

We start with the MACHO (Massive Compact Halo Object) project and its results. DM possesses the property of bending light creating what is called the gravitational lens effect. This experiment works with the microlensing. Microlensing surveys use gravitational lensing to detect a punctual mass that passes very close to the line of site. This effect has two signatures: The first result that microlensing should yield is an amplification of the detection power when the deflector crosses the line of sight to the source. This amplification is due to the conservation of the flux per solid angle and since the solid angle is augmented due to the multiple paths that the light has now the apparent flux also must increase. If we assume this effect due to baryonic DM candidates the amplification factor will be between 1 and 100 times. The second signature of the microlensing effect its achromaticity. There is no different refraction index for differ-

ent wavelengths because the lensing is due to curvature of space.
So, if the halo is composed by DM in form of planets, brown stars and black holes we should be able to detect this amplification effect for the light of extragalactic objects, the only problem is that the microlensing events are extremely rare and to see a few we would require a background field of approximately one million stars. There are two spots in our sky that meet this requirement, the LMC (Large Magellanic Cloud) and the GB (Galactic Bulge), this two where the focus of the MACHO Project. The project after 5.7 years of photometry on approximately 11.7 million stars in the LMC found 13 gravitational microlensing events, which is too little to explain all DM we need [11].

B. Non-baryonic

For this type of DM a lot of experiments, both in the field of astrophysics and in the field of particle physics, have been designed. In this paper, we will just present a few. First there is the observation of cosmic rays, which presents an upper limit called the Greisen-Zatsepin-Kuzmin limit (also called Ultra-GZK cosmic rays). This limit is thought to arise because of the interaction between the comic radiation and the microwave background over long distances, through annihilation and decay of superheavy DM, or as we have mentioned Wimpzillas.
One of the experiments focused on detecting WIMPs, that as we have talked are a prime DM candidate is the DRIFT (Direct Recoil Identification From Tracks) detector [12]. This detector consists on a cubical drift chamber filled with a low-pressure mixture of gases with which WIMPs will interact causing the nucleus to recoil. The results with this technique are still inconclusive, so new models and new DRIFT detectors are being created to achieve a more precise result.
We also have the satellite GAIA, from the ESA (European Space Agency), that is currently mapping our galaxy by surveying more than a thousand stars. This satellite allows us to observe the large-scale motion of the stars in the galaxy that will prove the distribution of DM. With the first mappings arriving late summer 2016 scientists are still studing the implications it has on the distribution of DM in the Milky Way, and hopfully prove the existence of dark-photon interacting DM concentrated in a thin DM disk.

VI. CONCLUSIONS

Through this paper we have reviewed the astrophysical/cosmological evidences of the existence of DM, since theories that modifies gravity have yet to demonstrate their veracity or have been debunked. Also, we have seen that such matter cannot be baryonic since it would oppose the primordial nucleosynthesis, so it must be beyond the SM. This type of non-ordinary matter has yet to be detected despite all the experiments. On the other hand, the SUSY particles have also failed to provide any experimental prove that works. Currently all hopes to find dark matter lie on axions or the direct detection of particles beyond SM (BSM), for instance by studying the b-meson discrepancies in the LHC. Alternatively the presence of a DM disc in the galaxy would demonstrate more exotic form of DM beyond the SM.
In conclusion, I have found the DM a far deeper problem that I first anticipated since I have seen that it involves almost every current branch of physics. That being said I do believe that DM is the answer to the observations, instead of the multiple correction of the gravity theories. The main problem I see right now are the experiments because of their slim range of study and the fact that most of them take too long, making the experiment almost unrepeatable, which pushes the scientific method to its limit.

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