Dark Matter: Evidence and Candidates

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ABSTRACT
Dark matter is one of the most mysterious subjects in cosmology. When people try to analyse the characteristic of a kind of object that they cannot observe it directly, how will they do? Just like the invisible dragon in Carl's gauge, when we cannot observe an object, how can we ensure that it exists. This essay will introduce why scientists need dark matter, what makes it important, and how scientists use ingenious methods to observe dark matter indirectly. In addition, scientists are always curious about what can be the candidates of dark matter. In this essay, the special characteristic of dark matter that make it different from the normal matter will also be introduced. These properties are essential to determine what can be dark matter and what cannot be. A lot of hypothetical particles and celestial body will be important candidates.

Keywords: *Dark matter, Cosmology, Evidence, Candidates*

1. INTRODUCTION

We, humans, have five ways to observe and explore the world: to hear, to see, to touch, to smell, and to taste. As society improves, many new technologies now can help us widen the kinds of objects that can be detected and predicted. For example, our eyes can only receive light with a wavelength between 390nm and 780nm, but Photoelectric Detector can help us to see the light. However, people still have very few ways to observe the universe. What humans see is only part of the "real universe" because of the limitation of the observing methods.

Carl Sagan has a very famous story, "The Dragon in My Garage". There is a dragon in a garage, which is invisible, untouchable, and floating in the air; whose fire is also invisible and heatless. Anyway, any physical tests would not prove that there is a dragon. However, there is! The invisible dragon in modern physics is Dark Matter (DM). According to Occam's Razor, entities should not be multiplied unnecessarily. If DM is hypothetical, it definitely makes the whole universe much more complicated, unless it is irreplaceable.

2. EVIDENCE

The earliest observance of Dark Matter was in 1933. When Zwicky used the Virial theorem combined with the redshift to count the dynamical mass of Coma Berenices, he found that the value was much bigger than the luminosity mass. To explain the difference, he hypothesized that there was a large amount of matter that do not emit light. Though most scientists didn't believe in this theorem, this was the first origin of DM.

The first valid evidence is from the galaxy rotation curve (GRC) (see figure 1). A GRC is a graph that describes the relationship between the orbital speed of stars and the relative distance from the centre of the galaxy. The rotational velocity v of an object like $\nu(r) \propto \sqrt{M(r)/r}$. The first GRC was made by Rubin and Kent Ford. They mainly studied the Andromeda Galaxy, using a new spectrograph developed by Ford [1] . When they finished mapping the graph, surprisingly, the speed didn't change much as the stars were away from the centre, i.e., the speed was extremely faster than the expected value predicted by the Newtonian or relatabilities' gravitation theory. In our cluster, $\nu \simeq 240\ km/s$ [2]. Traditionally, people believe that when stars are far away from the center of the galaxy, the orbital speed should be very slow, otherwise they will be thrown out of the galaxy. The big difference leads to a choice: whether the gravitation theory is wrong and needs to be modified, or there exists a kind of invisible matter in the galaxy that exerts a force on the stars.

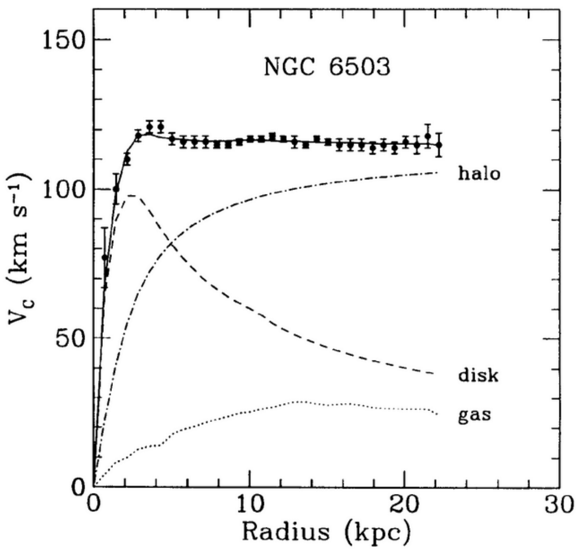

Figure 1. galaxy rotation curve (GRC)

Both of the two theories were paid a lot of attention, people devote a lot of time studying them. On one hand, people who believe the traditional Newtonian gravity was somewhat wrong developed Modified Newtonian Dynamics (MOND). Using MOND, the complicated and excrescent DM was reduced from the theory [1].

On the other hand, the difference can be explained by the dark halo, which should have a density $\rho(r) \propto 1/r^2$ Therefore, the mass density of DM is $\Omega_{DM} \leqslant 0.1$, and $\Omega_X \equiv \rho_X/\rho_{critical}$. $\rho_{critical}$ is the critical mass density. Many people believe the MOND theory, but later, many new theories needed the existence of DM.

Firstly, the observational data of the Gravitational lens effect of clusters supported that DM was essential. The Bullet Cluster of galaxies (1E 0657-558) consisted of two clusters, which are colliding. In the observance of the Bullet Cluster, it shows that between two colliding galaxies, the distribution of visible baryonic matter is far from the distribution of the DM. The former one is observed by detecting the X-ray and the latter one was detected using the Gravitational lens effect. This difference indicates that visible matter only occupies a very small proportion of the cluster [3]. This phenomenon is easily explained by DM. Though the MOND theory is also useful to explain it, it is so complicated that most physicists don't believe MOND.

Though the two pieces of evidence are very convincing, there are serval limitations. In order to comprehensively prove the existence of DM, we still need evidence of three aspects. First, the two pieces of evidence above only prove DM exists in some clusters, so large-scale evidence is essential. Secondly, neither of the two pieces of evidence can tell if DM exists in the early universe. In addition, they cannot tell us the exact amount of DM in the universe. Cosmic microwave background radiation (CMB) then becomes the best explanation that can explain the questions above. As most people believe, it is the Big Bang that "create" the university. CMB is just the residual radiation brought by the Big Bang, and it includes the information of the universe [3]. Currently, the Plank experiment can acutely measure the CMB thermometric anisotropy spectroscopy. In the data from Plank 2018, it is obvious that there are three very obvious peaks, in which the second and the third peaks are closely relative to the DM [4].

3. CANDIDATES OF DM

To determine the candidates, the characteristics of DM are essential. First, DM must have existed in the early universe, since this is the result of the CMB. In addition, DM must be stable, because it has been staying in the universe with little change. What's more, DM cannot participate in electromagnetic interaction, or in other words, DM must have no electric charge, for DM cannot interact with light. Otherwise, DM will be easily observed. DM cannot also participate in the strong interaction, i.e., DM doesn't have a color charge. This is because DM needs to be stable, and if DM is hadron, its stability acquires its mass to be small enough to prevent DM from decaying into other hadrons. However, in any experiment, we didn't find such "light" hadrons. Finally, DM must be non-relativistic, meaning that the mass is much bigger than the kinetic energy. To cover all the properties, DM is obviously not any of the particles in the Standard Model. Luckily, some theories that beyond the Stand Model can help us solve the problems.

3.1. Axion

Axion is a hypothetic particle. It is created to solve the strong CP problems. It is very light. This property seems to be against that of DM, but axion is also non-thermally produced. Many physicists believe axion may be the component of cold DM. when the temperature is much higher than the QCD phase transition, the mass of axion is zero [5]. The axion field at that time, however, can take any value within the limits of θ. Meanwhile, when the temperature is very low, i.e., the temperature is lower than 1GeV, the mass of axion will be $m \sim m\pi$ $(f\pi/f)$.

Currently, the only experiment to detect axion is in University of Washington: Axion Dark Matter eXperiment (ADMX). In the experiment, two models of axions were found: Dine-Fischler-Scrednicki-Zhitnitsky (DFSZ) and Kim-Schifman-Vainshtein-Zakharov (KSVZ) (see figure 2). Between the two models, DFSZ is more difficult to detect. It is because KSVZ has bigger order of signals. In a strong magnetic field, using the alpha to gamma conversion can detect the axion [6].

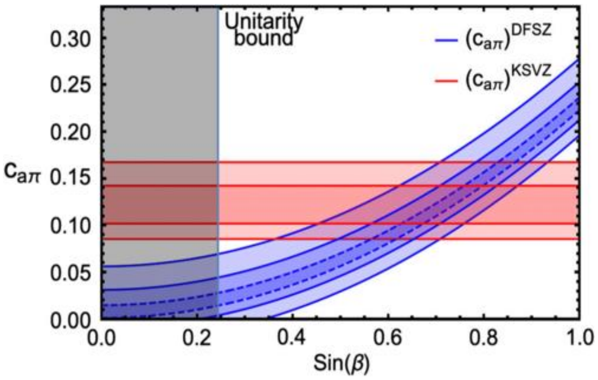

Figure 2. The axion-pion coupling caπ for the KSVZ (red) and DFSZ (blue) models.

3.2. WIMP

Weakly interacting massive particles (WIMP) (see figure 3) is the second candidate. It has two characteristics. Its mass is heavy than the particles in the SM, and only wear force and gravitation force can exert on it (or its cross-section force is smaller than the weak force). WIMP has mass between 10 GeV and serval TeV. Because WIMPs density is exponentially compressed when WIMPs are in chemical and thermally equilibrium with the particles in the SM after inflation, we can calculate the relic density currently of WIMPs.

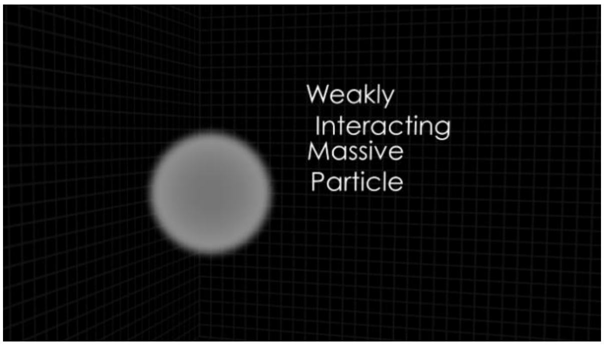

Figure 3. Weakly interacting massive particles (WIMP)

The candidate of WIMP used to be heavy neutrino, which seems to satisfy all conditions. However, heavy neutrino has a mass that is heavier than Mz/2, according to LEP data, its relic density will be too small. It is true that the relic density can be increased by mixing a heavy SU(2) doublet and some sterile neutrino [7]. However, don't forget that the DM cannot participate strong interaction, because it needs to be very stable.

Now, the most famous candidate of WIMP is the lightest superparticle (LSP). R-parity is the characteristic of LSP. LSP doesn't participate in the electromagnetic or strong interaction. Experiment has proved that LSP can only be neutral. There are two candidates that can satisfy this rule: sneutrino and neutralino [8]. After research and experiment, the result shows that "ordinary" sneutrinos compose most of the DM halo. In addition, after acute calculation, the relic density lightest neutralino achieve the desired value [7].

Because WIMP should be gravitationally trapped inside galaxies and should have the adequate density profile to account for the observed rotational curves, the main feature of experimental detection of WIMPs have been determined. Therefore, we can use these features to do WIMP serch.

There are a lot of experiments nowadays, including DAMA, XENON1T and PANDAX. Though they didn't directly detect DM particle, recently XENON1T claimed that they found some new evidence of the existence of DM. They found some abnormal facts. However, the experimental confidence is lower than the standard. We still need other evidence to prove.

3.3. Other candidates

3.3.1. Wimpzilla.

This word comes from Godzilla, meaning that this kind of particle is very big. Its mass is around 1012 TeV. Different from normal WIMP, it can be decayed from other particle, or produced thermally in the universe after inflation. Unlike WIMP, which used to have abundant amount and decrease until it cannot decrease. However, no practical method can properly detect Wimpzilla.

3.3.2. Primordial Black Hole.

This candidate is different. All other candidates we've mentioned are particles or matters, but Primordial Black Hole (PBH) (see figure 4) is celestial body [1]. Unlike black holes formed by the collapse of stars, primordial black holes were born in the very early universe. It is believed that the universe underwent a process of inflation within seconds of its birth formula. Inflation creates primordial density perturbations, and if a region is perturbed large enough, it can collapse to form primordial black holes [9].

Figure 4. Primordial Black Hole (PBH)

According to Hawking radiation, the mass of the PBH will be gradually decreased. therefore, many physicists believe that they are not DM because they are not stable enough. However, after detailed calculation, the PBH that has mass bigger than 109 Tons can still live today after around 14 billion. The limitation of the DM is very strong. For example, if the mass of PBH is similar to that of sun, the data shows that they can only compose one percent of the DM. Nowadays. In addition, current experiments have no restrictions on the mass between 10-12 times of the solar mass and 10-16 times of the solar mass. If experiment in the future can constrain the mass in that range, we can exclude the possibility that PBH is DM [10].

4. CONCLUSION

Though physicists have done a lot of effort, the existence of DM is still doubtful. The invisible dragon in the gauge is still hypothetical. Through the history of DM study, people are solving one problem: whether the existence of DM is reasonable. When it first appears, it seems to be an appendix of the cosmology theory. It is just like to go westward in order to reach east. However, many observances have proven that the validity of the DM; the fastest way to the east seems to be the road toward the west. If the DM is proven to be right by some valid experiment, the whole current cosmology model would experience a big change, even revolution.

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