

The Recent Progress of Dark Matter Detection and State-of-art Detectors

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Abstract. Dark matter is likely to be the main component of the universe, but it doesn't belong to any part of known substances, which make up the visible celestial bodies. Although dark matter has not been observed directly, there is a large quantity of evidence showing that dark matter does exist. This paper showed several typical candidates and evidence for dark matter and analysed their limitations, including WIMPs, axion, and PBHs. With respect to detection method, Migdal's effect is used as an example for direct detection and MAGIC telescope for indirect detection. For the observation evidence, the rotation curves, galaxy clusters, and cosmic microwave background are chosen as evidence. According to the analysis, though no dark matter has been already searched till now, it is believed that some promising candidates, (e.g., primordial black holes) exist in the universe. These results shed light on the future research for the property and formation mechanism for dark matter.

Keywords: Dark matter, dark energy, dark matter detection methods.

1. Introduction

The origin of dark matter can be traced back to late nineteenth century. British physicist Lord Kelvin presented the results of observing the stellar velocities, and he was thought of as the first to guess the existence of dark matter [1]. However, dark matter had not been given its name until in 1906, when French physicist Henri Poincare analysed Lord Kelvin's results and gave the name "Dark Matter". In 1915, Estonian physicist Ernst Opik analysed the vertical motions of stars and found that these can be explained by the spatial density of all known stellar populations [2]. Since 1922, Dutch astronomer Jacobus Kapteyn and English physicist James Jeans successively made similar analyses of vertical motion of the stars as Ernst Opik. Kapteyn concluded that the amount of invisible matter in the solar neighbourhood is small, and Jeans found that some dark matter may exist near the sun [2]. Subsequently, the focus of the observation of dark matter has moved from local dark matter to global dark matter, typically with the results from Swiss American astronomer Fritz Zwicky and American physicist Horace Welcome Babcock. In 1933, Zwicky studied the redshift of various galaxy clusters and observed that the radial velocities of eight galaxies in the Coma Cluster is amorously large [3]. On this basis, Coma Cluster, Zwicky analysed the mass of the cluster and estimation presented significant evidence for dark matter.

As an increasing number of evidence shows that dark matter occupies the majority of the universe, the technology of detecting dark matter such as state-of-art detectors and MAGIC telescope is also developing rapidly. With the help of these technologies, a number of observations since 1980s supported the existence of dark matter.

The rest part of this paper is organized as follows. The second section will focus on the definition and come popular candidates of dark matter. The third section will introduce some widely used detection method of dark matter. The fourth section will present some results of detection by using methods in the section 3. The fifth section will analyse the limitations of current research and give prospect and directions for future research of dark matter. The last section will conclude the importance and necessity of research for dark matter.

2. Basic Information of Dark Matter

2.1 Definition and Properties of Dark Matter

Generally, “dark matter” is defined as all component in the universe which are invisible but still obey the scaling. Based on this property, several candidates of dark matter are proposed.

2.2 Candidates of Dark Matter

In general, there are plenty of categories of dark matter. This paper will focus on the discussions for weakly interacting massive particles (WIMPs) such as neutrinos, axion, and primordial black holes (PBHs).

2.2.1. WIMPs

The first hypothesized candidate for dark matter is what is called Weakly Interacting Massive Particles (WIMPs). “Weakly interacting” means that the interaction is through weak nuclear force, and this property explains why one rarely sees them. Observations and calculations prove that dark matter should be not only (sub)weakly interacting but also non-relativistic and massive [4], which means dark matter is made up of WIMPs. Although WIMPs have not been observed directly, freeze-out mechanism has proved its existence. Freeze-out mechanism means that as the universe expands and cools, WIMPs finally froze out of thermal equilibrium, thus generating the dark matter. Neutrinos, a kind of WIMP, are formed by the decaying of a free neutron. Neutrinos are likely to be candidates for hot dark matter because they have mass and weakly interact with light with high velocity. Typically, sterile neutrino with mass in the keV range can play the role of dark matter [5].

Regarding the detection of WIMP, it is useful to consider how much kinetic energy can end up in a target nucleus. While restricting a WIMP mass range to 10-1000 GeV, it can be derived that

$$\frac{1}{2} m_{\tilde{\chi}} v^2 = \frac{1}{2} m_{\tilde{\chi}} c^2 \left(\frac{v}{c}\right)^2 \sim 2.7 - 270 \text{keV} \quad (1)$$

i.e., detectable energies have to be in the keV range.

2.2.2. Axion

In theoretical Physics, Quantum chromodynamics (QCD) is a standard model which describes the interaction between quarks which make up the strongly interacting particles (hadrons). QCD is able to uniformly describe the structure of hadrons and the interactions between them, hence it is considered as one of the most promising fundamental theories of the strong interaction. QCD theory possesses a strong CP problem, where CP stands for charge conjunction. The question that why electric dipole moment (EDM) hasn't been observed for neutron is known as the CP problem [6]. The existence of axion can explain the CP problem, and thus axion is thought of as another leading candidate of dark matter.

Axion is a kind of very light neutral particle associated with the joint symmetry breaking of charge conjunction-parity inversion in the strong interaction. Axion's interactions are set by its pseudoscalar nature where a pseudoscalar field changes sign under a parity transformation [6]. These certain interactions can be expressed by the non-relativistic Hamiltonian:

$$\mathcal{H} = \sqrt{\frac{\epsilon_0}{\mu_0}} g_{a\gamma\gamma} \int \mathbf{a} \cdot \mathbf{B} dV + g_{\text{aff}} \hbar c \nabla \mathbf{a} \cdot \hat{\mathbf{S}} + \sqrt{\epsilon_0 (\hbar c)^3} g_{\text{EDM}} \mathbf{a} \cdot \mathbf{E} \quad (2)$$

2.2.3. Primordial Black Holes (PBHs)

Through the detection of gravitational waves, primordial black holes (PBNs) become another promising candidate of the dark matter [7]. PBH is a hypothetical type of black hole which formed soon after the Big Bang. A fluctuation in the variety of the cosmos, including its gravitational collapse, is required for the formation of a primordial black hole. Ref. [7] shows that the abundance $\beta(M_H)$ of PBHs can be shown by

$$\beta(M_H) \equiv \frac{\rho_{PBH}}{\rho_{tot}} = \int_{\delta_c}^{\infty} p(\delta) d\delta \sim \sigma(M_H) \exp\left(-\frac{\delta_c^2}{2\sigma^2(M_H)}\right) \quad (3)$$

where $p(\delta)$ is the probability distribution of primordial density perturbations, and $\sigma(M_H)$ represents the mass variance.

3. Detection Method of Dark Matter

3.1 Direct Detection: Migdal's Effect



Figure 1 MINOS neutrino detector is a laboratory expanded by the University and the Minnesota Department of Natural Resources to accommodate physics projects [8].

Consequently, if one of these particles collides a nucleus of the matter in the detector, then the detector is able to observe the change in the nucleus's energy. Based on analysing the process of the collision, the properties of dark matter can be found. Most of detection apparatus are build underground to minimize the interference from cosmic rays to guarantee the efficiency of experimenting. As shown in Fig.1, underground laboratories such as MINOS detector are widely used to do direct detection of the dark matter.

In previous experiments using direct detection methods, the atomic electrons around the nucleus of the target material are usually assumed to immediately follow the motion of recoil nucleus [9]. However, the electrons actually tend to spend some time to catch up that motion. This phenomenon is called as Migdal's effect, which causes the ionization and excitation. The Migdal effect is reformulated by taking plane waves of the whole atomic system as the asymptotic states for the scattering process [9]. Moreover, a numerical analysis of the ionization and excitation rate of isolated atoms (e.g., Ar, Xe, and Ge) is done, and the results are applied to the experiments by using a liquid Xe detector as an example. Then, the conclusion can be drawn that the relatively light dark matter detectability can be improved by the final state ionization or excitation through elastic nuclear scattering [9].

Besides elastic nuclear scattering, the concept of inelastic scattering also provides instructions for low mass dark matter direct detection experiments. Ref. [10] calculated the electron recoil spectrum which is given by

$$\frac{d^2R}{dE_R dv} \propto \frac{m_\phi^4}{(m_\phi^2 + 2m_A E_R)^2} \frac{m_A}{2\mu^2 v^2} [vf(v)] F^2(q) \quad (4)$$

and concluded that this spectrum is caused by Migdal effect with respect to inelastic dark matter scattering. It is the Migdal effect that allows xenon-based detectors to be more sensitive to light dark matter.

3.2 Indirect Detection: MAGIC Telescope



Figure 2 The first MAGIC telescope locating at the Roque de los Muchachos Observatory [11].

Indirect detection focuses on the products caused by such self-annihilation or decay of dark matter particles in the outer space, including high-energy gamma rays, positive and negative electrons, protons and antiprotons, neutrons, neutrinos, and various cosmic ray nucleons.

From December 2014 to April 2016, the MAGIC, as shown in Fig. 2, conducted a deep observation campaign on UMaII, which is considered as one of the most dark-matter-dominated system among the Milky Way satellites [11]. After analysing the data, cleaning the images, doing mathematical parameterization, and using likelihood analysis, the constraints on the cross-section of distinct channels are obtained [11]. Afterwards, during 2018, MAGIC telescope is used to detect dark matter decay signals from the Galactic Halo. The procedure is to make a comparison between different sets of observation results conducted at different angular distances from the Galactic center that are selected in a way where all the diffuse components cancel out except for those coming from the dark matter [13]. After the likelihood analysis based on the data collected through 20 hours, a value of 4.8% which is independent of energy is obtained.

4. Observation Evidence of Dark Matter

4.1 Electromagnetic Field and Rotation Curves

In general, the mass density of a spiral galaxy is inversely proportional to its distance from the center if the outskirts. Observed rotation curves tend to be characterized by a flat property at large distance, which means they are far beyond the edge of the visible disks [14].

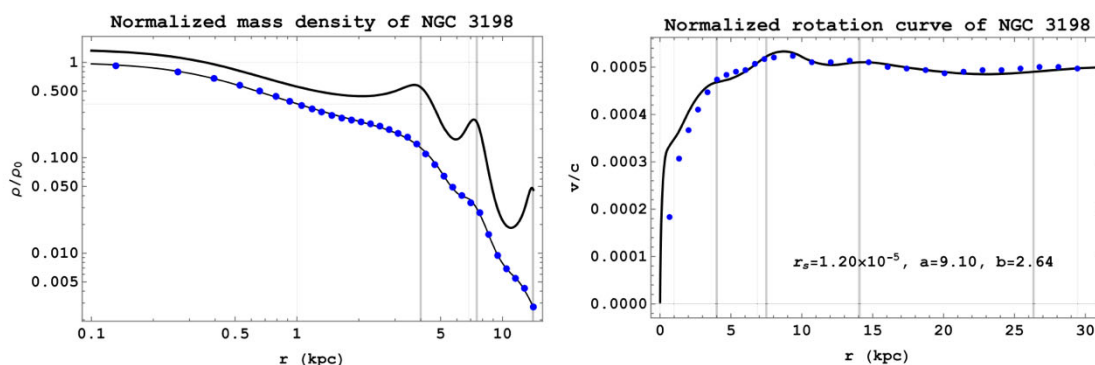


Figure 3 The mass density and velocity as a function of luminosity for dwarf galaxy NGC 3198 [15].

Most theoretical explanations of rotation curves used to focus on the Newtonian potential frame without taking the general relativistic corrections with mass currents into consideration [15]. Ludwig combined the effect of both Newtonian potential and gravitomagnetic field and found a nonlinear differential equation which described the relationship between the rotation velocity and the mass

density. The solution of this differential equation showed again that galactic rotation curve without resource to obscure dark matter components [15]. Moreover, as shown in Fig. 3, the normalized mass density and rotation curve of the observed dwarf galaxy also provide evidence for the results of the differential equations. Therefore, taking electromagnetic field into account can explain the existence of dark matter more precisely.

4.2 Galaxy Clusters

It is believed that the heavier a galaxy cluster is, the darker matter it contains. The mass distribution of galaxy clusters can be obtained by three independent ways: observe the motion of the galaxies in the galaxy clusters and calculate the mass distribution by gravitational theory; observe the x-ray generated by galaxy clusters and predict the mass distribution by its temperature; use the bending degree of the background light observed by gravitational lensing to calculate the mass distribution.

According to the 12 years of Fermi/LAT data of five nearby clusters that are expected to be the strong sources of high energy photons, the models of dark matter halo of each cluster are made [16]. Such models clearly show the distribution of dark matter in the clusters' samples.

4.3 Cosmic Microwave Background

Based on the observation and calculation of cosmic microwave background radiation, the total amount of the dark matter in the universe can be evaluated. Dark matter not only interacts with radiation but also affect cosmic microwave background by its gravitational potential. The cosmic microwave background (CMB) strictly limit the models of dark matter and the initial conditions of the universe [17]. To be specific, it uses the latest Planck CMB data to present the limits of a mixed dark matter model where a component of the dark matter resides in a ultralight axions (ULA).

Over the past two decades, CMB has become a powerful probe of astrophysics on account of its well-performance properties (e.g., easily measurements) [18]. As a result, CMB is useful to establish new models and observe cosmological phenomenon. In the latest five years, researchers mainly explore the universe in two ways with the CMB: gravitational lensing and the kinetic Sunyaev-Zel'dovich (kSZ) effect [18]. Gravitational lensing can be used to connect the masses of galaxies and clusters to the CMB fluctuations, and the kSZ effect allows for the observation of the universe's motions. Such technologies help to make a great progress of the study of dark matter.

5. Limitations and Prospects

Although there are many sophisticated detection method and apparatus for dark matter observation, limitations and constraints still exist. Firstly, the most challenging problem is that none of the detection methods can observe dark matter straightforwardly. Although there are a number of evidence implying the existence of dark matter, all such information is based on hypotheses and calculation. Secondly, even there are theories and models supporting the promising candidates such as WIMPs, axions, PHBs as dark matter, the specific component of dark matter hasn't been confirmed. Thirdly, not all evidence of observation is always in accordance with the theoretical calculation, and the detection equipment can also be unconvincing. For example, direct detection experiments are largely blind to sub-GeV dark matter [19].

The study of dark matter lasts for more than one century, but dark matter still cannot be seen directly. As a consequence, it is necessary to improve the research methods and observation methods from now on. Firstly, the calculation of dark matter should not only focus on the energy and mass density of dark matter but also care about other physical quantities, e.g., momentum, angular momentum (spin), and electromagnetic field. More background data means more reference for analysis and prediction. Secondly, it is essential to diversify the experimental effort and to test the properties of dark matter [20]. Last but not least, larger energy range should be searched by updating the facilities, and the resolution of the pictures observed from the telescope should be improved to get clearer figures.

6. Conclusion

In summary, this paper demonstrates the dark matter from the perspectives of the definition, candidates, detection methods, detection evidence, and limitations. The most promising candidates for dark matter are WIMPs, neutrinos, axion and PBHs. Both direct and indirect detection methods (e.g., Migdal's approach and MAGIC telescope) are still developing nowadays. The evidence observed by detectors strongly proves the existence of dark matter, but there still exist some limitations, e.g., the lack of detection for sub-GeV dark matter. However, such limitations provide future research directions, indicating that the detection experiments should be improved and diversified. Overall, these results offer a guideline for future exploration of dark matter.

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